A Best Effort QoS Support Routing in Mobile ad hoc Networks

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Abstract

In the past decades, mobile traffic generated by devices such as smartphones, iphones, laptops and mobile gateways has been growing rapidly. While traditional direct connection techniques evolve to provide better access to the Internet, a new type of wireless network, mobile ad hoc network (MANET), has emerged. A MANET differs from a direct connection network in the way that it is multi-hopping and self-organizing and thus able to operate without the help of prefixed infrastructures. However, challenges such dynamic topology, unreliable wireless links and resource constraints impede the wide applications of MANETs.

Routing in a MANET is complex because it has to react efficiently to unfavourable conditions and support traditional IP services. In addition, Quality of Service (QoS) provision is required to support the rapid growth of video in mobile traffic. As a consequence, tremendous efforts have been devoted to the design of QoS routing in MANETs, leading to the emergence of a number of QoS support techniques. However, the application independent nature of QoS routing protocols results in the absence of a one-for-all solution for MANETs. Meanwhile, the relative importance of QoS metrics in real applications is not considered in many studies.

A Best Effort QoS support (BEQoS) routing model which evaluates and ranks alternative routing protocols by considering the relative importance of multiple QoS metrics is proposed in this thesis. BEQoS has two algorithms, SAW-AHP and FPP for different scenarios. The former is suitable for cases where uncertainty factors such as standard deviation can be neglected while the latter considers uncertainty of the problems.

SAW-AHP is a combination of Simple Additive Weighting and Analytic Hierarchical

Process in which the decision maker or network operator is firstly required to assign his/her preference of metrics with a specific number according to given rules. The comparison matrices are composed accordingly, based on which the synthetic weights for alternatives are gained. The one with the highest weight is the optimal protocol among all alternatives. The reliability and efficiency of SAW-AHP are validated through simulations. An integrated architecture, using evaluation results of SAW-AHP is proposed which incorporates the ad hoc technology into the existing WLAN and therefore provides a solution for the last mile access problems. The protocol selection induced cost and gains are also discussed. The thesis concludes by describing the potential application area of the proposed method.

Fuzzy SAW-AHP is extended to accommodate the vagueness of the decision maker and complexity of problems such as standard deviation in simulations. The fuzzy triangular numbers are used to substitute the crisp numbers in comparison matrices in traditional AHP. Fuzzy Preference Programming (FPP) is employed to obtain the crisp synthetic weight for alternatives based on which they are ranked. The reliability and efficiency of SAW-FPP are demonstrated by simulations.

Declaration of originality

I hereby declare that the research results presented in this thesis and the thesis itself were composed and originated entirely by myself in the Department of Electronics and Electrical Engineering at the University of Edinburgh, unless explicitly stated otherwise.

Heng Luo

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I would like to take this time to thank those who assisted me through the period of this work. My supervisor D. I. Laurenson gave me very valuable suggestions and encouraged me for a number of times. I also want to thank my parents who provide financial support and my wife who delivers my lovely daughter.

Acronyms and abbreviations

ADSR	Associativity-based Dynamic Source Routing
AHP	Analytic Hierarchy Process
AODV	Ad hoc On-demand Distance Vector
AQOR	Ad hoc QoS On-demand Routing
BER	Bit Error Rate
CR	Consistency Ratio
DARP	Defence Advanced Research Projects
dBM	dynamic Bandwidth Management
DSDV	Destination Sequenced Distance Vector protocol
DSR	Dynamic Source Routing
EAM	Extent Analysis Method
EDTORA	Energy and Delay aware TORA
ELECTRE	ELimination Et Choix Traduisant la Réalité
FCS	Frame Control Sequence
FGMM	Fuzzy Geometric Mean Method
FLLSM	Logarithmic Least Squares Method
FPP	Fuzzy Preference Programming
GRA	Grey Relational Analysis
MANET	Mobile Ad hoc NETwork
MAUA	Multi-attribute Utility Analysis
MCDM	Multi-Criteria Decision Making
MLLSM	Modified LLSM
MQR	Multipath QoS Routing
MT	Mobile Terminal
NP	Nondeterministic Polynomial time

OLSR	Optimized Link State Routing Protocol
PBR	Partial Bandwidth Reservation
PER	Packet Error Rate
PIR	Performance Improvement Ratio
PLCP	Physical Layer Convergence Protocol
QAMR	QoS-Aware Multipath Routing
QAODV	Qos AODV
QLLI	QoS aware Lower Layer Information Routing
QoE	Quality of Experience
QoS	Quality of Service
QRMR	QoS-based Robust Multipath Routing
RI	Random Inconsistency index
RQG	Routing protocol with QoS Guarantees for ad hoc network
RREP	Route REPly
RREQ	Route REQuest
RSVP	Resource Reservation Protocol
RWP	Random WayPoint model
SAW	Simple additive Weighting
SAW-AHP	Simple Additive Weighting and Analytic Hierarchy Process
SBR	Signal-to-interference and Bandwidth Routing
SINR	Signal to Interference and Noise Ratio
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TORA	Temporally-Ordered Routing Algorithm
VoIP	Voice over IP

Nomenclature

η	end-to-end throughput
P_{ed}	payload of effectively delivered data packets
$t_{elapsed}$	elapsed time
τ	Delay
t_S	processing time at source node
t_D	processing time at destination node
$\Delta\tau$	jitter
α	packet delivery ratio
$ENDP$	number of effectively received data packets
$TNTP$	number of total data packets
E_c	energy consumption
OEC	overall energy consumption
$ENDP$	number of successfully received data packets
$P_r(i)$	signal strength of $i^{'th}$ packet
$P_r(m)$	maximum signal strength
P_{noise}	power of noise
$BER_{BPSK}^{8\times 24}$	bit error rate of BPSK modulation
$BER_{modulation}^{8\times(28+L)}$	bit error rate for payload
w_t	width of the topology
l_t	length of the topology
N_n	number of neighbours
r	transmission range
a_{ij}	$ij^{'th}$numerical value in the comparison matrix
ω_i	weight for the i'^{th} element
$s\omega_j$	synthetic weight for the alternative j

s_j	the ideal solution
P_{target}	performance of target protocol
$P_{\text{reference}}$	performance of target protocol
$\mu_M(x)$	membership function
l	lower bound of the triangular fuzzy number
m	middle of the triangular fuzzy number
u	upper bound of the triangular fuzzy number
$\tilde{e}_{ij}$	comparison ratio of two elements.
β_{ij}	average value of performance
d_1	tolerance parameters
d_2	tolerance parameters
a_{target}	average value of performance for target protocols
$a_{\text{reference}}$	average value of performance for reference protocols
$\Delta_{\text{reference}}$	standard deviation for reference protocols
Δ_{target}	standard deviation for target protocols

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Chapter 1 Introduction

Wireless communication has witnessed faster growth worldwide compared to its traditional wired counterpart in the past decades due to the explosive use of mobile equipment such as smartphones, iphones, laptops, etc., and an increase of connection speed. Since its first introduction, a number of technologies (e.g., WiMAX, WLAN and WiFi) have emerged to improve the experience of wireless communications among which mobile ad hoc network (MANET) is an alternative.

1.1 Mobile Ad hoc Networks (MANETs)

A mobile ad hoc network (MANET) is an autonomous system composed of mobile nodes that are free to move about arbitrarily [1] as shown in Figure 1.1. This system may operate in isolation, or may have gateways to and interface with a fixed network. The capability of random movement for mobile devices leads to a dynamic and unpredictable topology change of the network. The source and destination may exchange information directly if they are within the transmission range of each other or through intermediate relaying nodes.

The possibility of deploying MANETs in scenarios such as disaster relief areas, military fields and emergency medical sites that are characterized by lack of preinstalled infrastructure justifies the development of such networks. More recently, MANETs have also been proposed or established in other realms such as vehicular communication and environment monitoring.

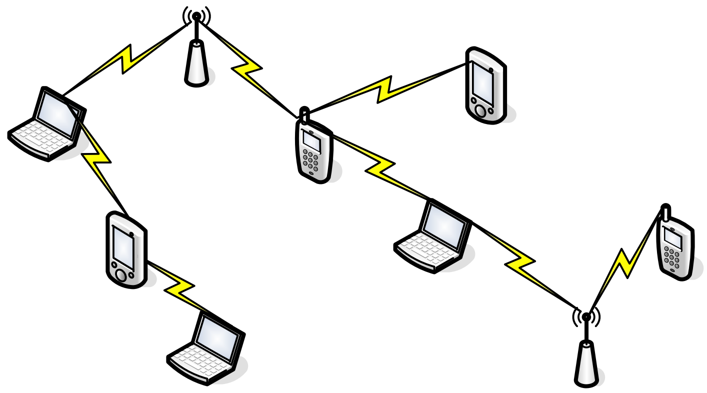


Figure 1.1 A mobile ad hoc network

Vehicular communication is an area where MANETs gain wide popularity. The FleetNet project [2] collects and shares location-dependent information for passengers. The European Project CarTALK [3] focuses on warning messages distribution when high traffic density, congestion, or dangerous road surfaces are detected in order to prevent potential traffic accidents.

In addition to vehicular communication, MANETs have also been implemented in the fields of environment monitoring. L. Laffea *et al.* [4] design and establish a MANET within a forest to study the movement of CO_2 so that the impact of forest-atmosphere CO_2 exchange can be estimated more accurately. The PermaSense project [5] depends on a MANET to gather data so that the understanding of the relationship between climate change and rock fall in permafrost areas can be improved.

Benefits are also obtained in the civil engineering through MANET technology. S. Kim *et al.* [6] design and deploy a MANET on the south tower of the Golden Gate Bridge in order to measure the ambient structural vibrations reliably without interfering with the normal operation of the bridge. A structure-aware self-adaptive system (SASA) [7] based on a MANET is realized to rapidly detect the collapse area in a coal mine, which makes mining safer.

In September 2007, the TerraNet AB Company [8] presented a mobile ad hoc network which allows calls and data to be forwarded between participating handsets without cell sites. P. Sikka *et al.* [9] establish a MANET on a farm to provide soil moisture profiles at varying depth and animal movement tracking so that the cost of managing farms is reduced. One Laptop per Child (OLPC) [10] is a project targeting the creation of educational opportunities for the world's poorest children by providing each child with a laptop. These laptops are organized through mobile ad-hoc networking which allows students to access the Internet and participate in collaboration.

1.2 Quality of Service (QoS)

In ITU-T Recommendation E.800 [11], the term quality of service is defined as “the collective effect of service performance, which determines the degree of satisfaction of a user of the service”. Intrinsic to the notion of QoS is a strict guarantee, so called hard QoS, of a number of measurable specifications, always in terms of throughput, delay, and jitter as well as packet delivery ratio.

Quality of service is not a new term in computer networks, but it did not attract much attention at during the early stages of Internet development. With the rising popularity of Quality of Service (QoS) sensitive applications such as multi-media and VoIP, the ability to provide QoS support becomes more crucial in today’s networks than it was in the past. However, the conventional Internet only provides best effort services in which packets are transmitted as quickly and reliably as possible. To provide QoS support, a set of mechanisms have been proposed in wired networks and they can be classified into two main categories, IntServ[12] and DiffServ [13].

The paradigm behind IntServ is resource reservation for every flow. Flow-specific state information is maintained to support two classes of services, the guaranteed service [14] for delay-sensitive applications and controlled load services [15] for reliability-sensitive applications. A typical and successful IntServ algorithm is Resource Reservation Protocol (RSVP) [16] which propagates the attributes of the data flow to request resources. Bandwidth is a commonly reserved resource in RSVP to realize QoS guarantees [17] [18].

While IntServ provides a per-flow guarantee, DiffServ follows the tenet of classifying multiple flows into a set of service levels. At the boundary of the network, traffic entering a network is classified by the service provider. A special DS (Differentiated Services) field is attached to the IP packet header (TOS field in IPv4 or TRAFFIC CLASS field in IPv6 [19]) based on which packets are forwarded within the core of the network.

1.3 Problem statement and motivation

Compared to wired communication, MANETs have several unique characteristics. To begin with, MANETs rely on wireless links to transmit packets and those links are dynamic compared to wire lines since they are subject to time and location dependent signal attenuation, reflection, refraction, diffraction, and interference. Another disadvantage of wireless links is limited bandwidth.

Furthermore, the topology in MANETs changes dynamically due to the unpredictable movement of nodes, which may cause network partitioning whereas in wired networks the topology seldom changes. As a consequence, protocols in MANETs have to cope with movement induced path breakages.

Last, but not least, some devices in MANETs are battery powered and thus energy consumption must also be taken into consideration in the network design. In wired networks, devices always have enough power and the energy constraint is rarely considered.

Due to the significant difference in MANETs, the mechanisms for wired networks can not be mapped to MANETs directly. QoS provision in MANETs is quite challenging and it involves actions in different layers within which the network layer plays a crucial role. The routing protocol in the network layer not only has to find a path, if any, that can satisfy QoS requirements at the beginning of a session but also needs to react to mobility induced route breakages. Numerous efforts have been devoted to addressing this problem, leading to the introduction of a series of QoS provision protocols with one or two QoS metrics support, always in terms of bandwidth and delay.

However, it is observed that many applications in real world usually have more than two QoS constraints simultaneously that are, sometimes, contrary [20]. To design a single protocol with two or more QoS constraints is known to be a NP-complete problem [21] [22] [23] and the time to solve a NP-complete problem using algorithms available currently increases dramatically as the size of the problem increases [24]. Meanwhile, routing protocols with diverse QoS metric support are application-dependent which means a new algorithm has to be implemented as the application or environment changes. Last, but not least, the relative importance of QoS metrics in applications is neglected in much literature. This motivates the development of a best effort QoS support (BEQoS) model which evaluates and ranks alternative routing protocols according to the relative importance of QoS metrics in a given scenario.

1.4 Thesis contributions

Several contributions regarding the BEQoS model, under multiple QoS requirements and its applications in system optimization are reported in this thesis. The main contributions include:

(I) A rigorous and accurate mathematical algorithm SAW-AHP, which combines simple additive weighting (SAW) and analytic hierarchical process (AHP), is proposed to evaluate the performance of DSDV and DSR in terms of QoS metrics in Chapter 4. Four QoS metrics, packet delivery ratio, delay, jitter and throughput, and one performance metric, energy cost, are included in this model [25]. The consistency of SAW-AHP is measured finally to ensure the consistency of the pair-wise comparisons. SAW-AHP is further extended to fuzzy SAW-AHP (FSAW-AHP) by replacing the crisp comparison results with fuzzy triangular numbers so that standard deviations in simulation are included in Chapter 5, increasing the accuracy of the ranking results. Fuzzy preference programming (FPP) is adopted to derive crisp weights from fuzzy triangular matrices in FSAW-AHP.

(II) A new metric synthetic improvement ratio, denoted by SIRI, is developed to measure the level of performance improvement or deterioration when a different routing protocol is selected in Chapter 4. A positive SIRI indicates an improvement while a negative one reveals deterioration of the performance. SIRI is also extended to FSIRI (fuzzy SIRI) and therefore the performance improvement or deterioration can be evaluated in the context of fuzzy logics in Chapter 5.

(III) An adaptive framework that applies a BEQoS model in mobile ad hoc networks for the extension of existing WLANs, using SAW-AHP algorithm, is proposed in Chapter 4. This mechanism includes a protocol selection trigger which activates the adaptive protocol selection process, protocol selection decision which determines the optimal protocol as well as protocol selection execution. This model is able to maximize the information usage of the access point while maintaining the user preference with regard to QoS metrics.

1.5 Organization of this thesis

The thesis is organized as follows:

Chapter 2

Research papers regarding single or multiple QoS requirements provision are reviewed in this chapter followed by a survey of multiple criteria decision making methods.

Chapter 3

This chapter provides a systematic and comprehensive description of the simulation setup, including simulation tools, node configuration parameters, the propagation model, the traffic generation pattern, the node mobility pattern, etc. Later in this chapter, two on demand routing protocols, DSR and DSDV, are simulated, followed by results analysis and discussion. Results from simulations are used as empirical knowledge in the BEQoS model.

Chapter 4

In this chapter, SAW-AHP is adopted to evaluate two alternative routing protocols DSDV and DSR with reference to four QoS metrics and energy cost. Two other multi-criteria decision making methods GRA and TOPSIS are compared with SAW-AHP. In addition, the consistency of SAW-AHP is addressed. The reliability of SAW-AHP is validated through simulations. A framework for adaptive mobile ad hoc networks with SAW-AHP is proposed. A discussion of cost for such an adaptive algorithm concludes this chapter.

Chapter 5

In this chapter, the standard deviation of protocol performance from simulations is considered and SAW-AHP is thus extended to fuzzy SAW-AHP. Two methods, FPP and FPP with a fuzzy extension of the geometric mean method, denoted by FGMM, are adopted to derive weights from fuzzy SAW-AHP. The former generates crisp synthetic weights for alternatives while the latter leads to fuzzy synthetic weights. Since FGMM results in different ranking orders, it is abandoned in this thesis. FPP is able to derive weights and rank alternatives reliably which is demonstrated via simulations and thus it is adopted.

Chapter 6

This chapter concludes the thesis and provides guidelines for future research.

Chapter 2 Background

In the early stages of MANET development, in the 1990s, QoS provision did not attract much attention and thereby most routing protocols operated on a best effort model. However, with the growing popularity of time-sensitive applications, QoS support becomes much more important than it was, leading to a shift of research interest from best effort routing to QoS provision routing. However, providing QoS guarantees in MANETs is quite challenging due to the dynamic topology, limited bandwidth and energy constraint. This chapter gives a background description concerning difficulties in QoS support over MANETs and surveys a number of QoS provision protocols. It is organized as follows. The first section itemizes some characteristics of MANETs and outlines some well-studied routing protocols. The following section gives a definition of QoS and formulae to calculate some QoS metrics. The third section reviews QoS routing in MANETs. Section 2.4 discusses the application dependent nature of existing QoS extensions. Section 2.5 outlines the performance evaluation techniques.

2.1 MANETs

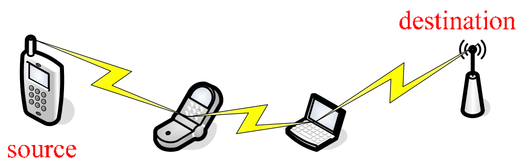
A mobile ad hoc network is a wireless network without centralized control where every node acts as a router, forwarding packets to the destination when necessary [26]. MANETs have several advantages over conventional wired networks. First of all, MANETs are very convenient. The operator doesn't have worries such as running wires in tight places or obtaining low-voltage permits [35]. Secondly, the deployment range of MANETs is impressive compared to wired networks whose length of wires run limited [35]. However, some valuable characteristics of wired networks (e.g., reliability, cost, speed) are traded off in achieving this.

2.1.1 Properties of MANETs

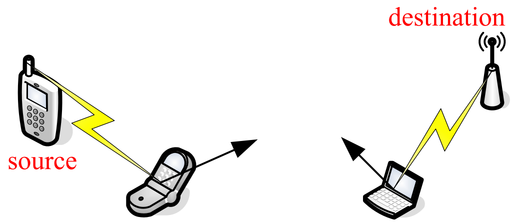
MANETs differ from their traditional wired counterpart in several aspects and they are itemized as follows.

(I) Dynamic topology

Nodes in MANETs may move arbitrarily which leads to a changing topology. This is quite different from traditional wired networks. Typically in high mobility applications like vehicular communication, topology changes rapidly. On one hand, dynamic topology may increases the cost of maintaining routes due to link breakages. On the other hand, node mobility may reduce the effects of network partitioning as shown in Figure 2.1



(a) Network partition



(b) Route establishment

Figure 2.1 Node mobility aided route establishment

Due to limited transmission range of radio and arbitrary movement of nodes, the wireless link becomes unpredictable and unstable, leading to difficulties in maintaining the route. Therefore, the MANET routing protocol should be capable of dealing route break besides route discovery.

(II) Unpredictable link quality

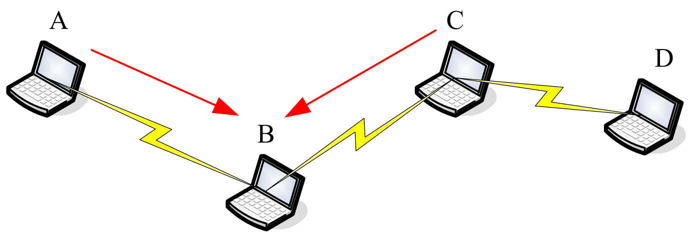
Wireless media is time and location dependent. Signals experience fading, interference and multipath cancellation during transmission [36]. In addition, wireless links have lower capacity than their wired counterpart, increasing the possibility of network congestion. Since MANETs are regarded as an extension of the existing wired network in many applications, the bandwidth problem should be considered. Unpredictable link quality, together with limited bandwidth makes providing bandwidth and delay guarantees a really challenging task.

(III) Limited energy resource

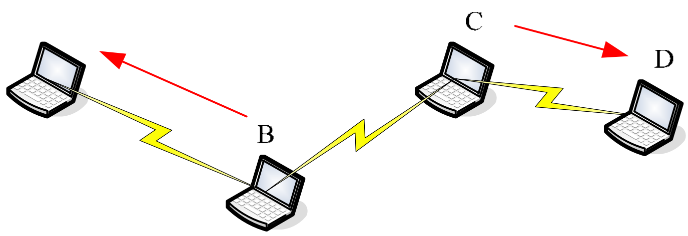
Many mobile devices in MANETs depend on batteries or other finite energy sources for their energy supply. Sometimes, frequent recharging or battery replacement may be undesirable or even impossible [27]. Therefore, many energy efficient protocols have been proposed in different layers, such as [28] and [29] in physical layer, [30] and [31] in link layer, [32] and [33] in network layer and [34] in transmission layer.

(IV) Hidden terminal problem and exposed terminal problem

The hidden terminal problem and exposed terminal problem are experienced frequently in MANETs. As shown in Figure 2.2(a), the hidden terminal problem happens when two nodes A and C stay out of each other's transmission range and send packets simultaneously to a same destination B. Those packets collide and thereby are dropped by node B. Figure 2.2(b) describes the exposed terminal problem. As seen, when node B is transmitting packets to A, node C has to defer its transmission for node D even if such transmission will not disturb the reception process in node A. RTS/CTS acknowledgement and handshake in 802.11 partly solve the hidden terminal problem at the cost of throughput reduction.



(a)Hidden terminal problem



(b) Exposed node problem

Figure 2.2 Hidden and exposed terminals

2.1.2 Routing protocols for MANETs

Routing is an important issue in networks. In wired networks, dynamic routing approaches are prevalent among which distance vector routing and link state routing are two of the most popular models [37]. Distance vector routing is based on the Bellman-Ford algorithm in which each node maintains a routing table including the distance to reachable destinations. This routing information is advertised periodically. The source adopts the shortest route when it has packets for a destination. In link state routing, every node propagates its current status of links to all reachable nodes. Whenever a link status in one node changes, a corresponding advertisement will be broadcasted based on the routing table which is refreshed.

In wired networks, both distance vector and link state routing behave well due to comparatively stable link quality and topology. However, properties such as link quality and topology in MANETs become unpredictable, degrading the performance of some distance vector and link state routes. As a consequence, protocols have been proposed and well studied, five of which are described below.

(I) Destination Sequenced Distance Vector protocol (DSDV)

DSDV [38] is a typical proactive routing protocol in which each node has to maintain a routing table for all available destinations. Routing updates are broadcast periodically. DSDV relies on a sequence number to indicate the freshness of the corresponding item to guarantee loop-freedom. When a route breakage between two nodes, say A and B, is detected by node A, it increases the corresponding sequence number and sets the distance to node B as infinite and this information will be further broadcasted.

In DSDV, the routing information broadcasts introduce a large number of control packets which increases the overhead. At the same time, it takes some time before a route can be used, the so called the convergence time [39]. In wired networks where the topology is comparatively stable, this convergence time is minor and it can be neglected. However, in a network where topology changes rapidly, the convergence time is sufficiently long that there will likely be a lot of dropped packets.

(II) Dynamic Source Routing (DSR)

DSR is a reactive protocol which establishes routes on demand [40]. It initializes a route request process when a route to the destination is not known in the route cache. Up on receiving a route request packet (RREQ) packet, intermediate nodes either generate a route reply packet (RREP) while it caches the corresponding route or it adds its own address to the RREQ and forwards the RREQ until it reaches the destination or the packet live time expires. Where bidirectional links exist, the reverse path will be used when the destination or intermediate node doesn’t have a route to the source in the cache. In the case of a route breakage, an error packet is generated by the node which detects it and the corresponding item in the route cache is erased.

Compared to DSDV, DSR doesn’t use periodic broadcasts and thereby reduces routing overhead, saves energy and partly eases network congestion. However, each data packet carries routing information in DSR, increasing the overhead.

(III) Ad hoc On-demand Distance Vector (AODV)

AODV [41] is a reactive protocol, based on the distance vector algorithm. The source in AODV originates a RREQ packet when a route to the destination is not available in the cache. The RREP packet is forwarded until it arrives at the destination or an intermediate node which has a fresh enough route. When a stale route is detected, the corresponding routing item is removed and a link failure message is sent out, triggering the route discovery process. HELLO messages are generated periodically to indicate the presence of a node to its neighbours.

Compared to conventional distance vector protocols, the number of advertisement packets in AODV is largely reduced. Two main disadvantages of AODV are HELLO induced routing overhead increase and an assumption of bidirectional links.

(IV) Temporally-Ordered Routing Algorithm (TORA)

TORA [42] is a reactive MANET protocol, aimed at minimizing routing overhead by controlling the receiving scope of routing messages when the topology changes. In TORA, each node is assigned a height. All messages flow downstream like water, from a node with a higher height to another one with a lower height. When a node happens to have packets for a destination but it has no downstream links, it broadcasts a Query (QRY) packet which will then be forwarded until it reaches a node that either knows a valid route or is the destination. Such a node will broadcast an update (UPD) packet containing its own height. Other nodes receiving this UPD packet will set their own heights with higher values compared with that in the UPD packet and broadcast this new height. In this manner, the route is established.

In TORA, only one route will be discovered even if multiple routes are available because each node only has one height value that is initially based on the distance from the destination [39].

(V) Optimized Link State Routing Protocol (OLSR)

OLSR [43] is a proactive routing protocol which utilizes Hello messages and Topology Control (TC) messages to discover and exchange link state information based on which individual nodes are informed about the next hop node for destinations.

Being a proactive routing algorithm, the route establishment time for OLSR is short since routes are known before use. Two disadvantages of OLSR are a potentially long convergence time, periodic information broadcast induced extra energy consumption and additional routing overhead.

Table 2.1 Comparison of protocols for MANETs

Property	Protocol				
	DSDV	**DSR**	**AODV**	**TORA**	**OLSR**
Loop-free	Yes	Yes	Yes	Yes	Yes
Reactive/Proactive	Proactive	Reactive	Reactive	Reactive	Proactive
Unidirectional link support	No	Yes	No	No	No
Power conservation	No	No	No	No	No
Adaptive	No	No	No	No	No
QoS support	No	No	No	No	No

Table 2.1 summarizes the five well-studied protocols described above. As seen, all of them are loop free, avoiding the waste of limited resources in MANETs. DSDV and OLSR are two proactive protocols and more energy and bandwidth are consumed for routing information advertisements. DSDV and OLSR are more suitable for slowly changing networks in which it takes less time to converge. DSR is the only protocol that supports unidirectional links. Although energy is of great importance for many mobile devices, it is not considered in all protocols. None of the protocols above are adaptive,

indicating that they do not contain any smart routing schemes. Meanwhile, it is observed that QoS issues are not considered in any of those protocols. With the development of MANETs, several adaptive protocols have been proposed [44][45][46]. However, only one or two QoS metrics are considered in those algorithms. For simplicity but without loss of generality, DSDV, a typical proactive routing protocol, and DSR, a typical reactive routing protocol, are selected as two alternative protocols for comparisons. In this way, the efficiency of the proposed adaptive algorithm can be observed clearly.

2.2 Quality of Service

As stated in last section, many routing protocols such as DSDV, DSR and AODV have paid little attention to QoS support in the early development of MANETs. However, QoS provision is becoming more important nowadays due to the rising popularity of real-time applications.

2.2.1 Rising necessity for QoS provision

In the past decades mobile traffic, which by definition refers to data generated by handsets, laptops and mobile broadband gateways, has been growing rapidly annually. According to a survey by Cisco, mobile data in 2010 was triple the volume of the entire global Internet traffic in 2000. The growth rate in the previous year was 159%, which is 10% higher than anticipated in 2009. This rapid growth in mobile data is forecast to continue for the next five years with an average annual growth of 92% [47].

There are several reasons why mobile traffic has grown so quickly. Firstly, mobile video, which requires high bit rates, is considered to lead to the increase of mobile traffic. It is reported that mobile video reached as high as 49.8% of total mobile traffic in 2010 and will account for two thirds of mobile traffic by 2015 [47]. Moreover, Internet gaming, which consumes, on average, 63 PB per month in 2009, also results in a growth in mobile traffic and it is expected to achieve an annual growth of 37% in the coming five years [48]. Last but not the least, Voice over IP (VoIP) which includes phone-based VoIP services direct from or transported by a third party to a service provider, and software-based internet VoIP such as Skype, leads to the expansion of mobile traffic. Many of those applications described above are real-time applications which demand certain guarantees for performance metrics for acceptable operation. Those metrics specify the Quality of Service.

2.2.2 QoS metrics

QoS is usually defined as a set of services that should be supported during packet transmission. A QoS enabled protocol is expected to support several metrics in terms of end-to-end throughput, delay, and jitter as well packet delivery ratio.

2.2.2.1 End-to-End Throughput

End-to-End throughput, η, is defined as the ratio of the payload of effectively delivered data packets, P_{ed}, over the elapsed time, $t_{elapsed}$.

$$\eta = \frac{P_{ed}}{t_{elapsed}} \tag{2.1}$$

the basic unit of η is b/s or B/s. Effectively delivered data packets refers to data packets that are successfully delivered, excluding any duplicated packets.

Since the available bandwidth in a network is fairly well known, it is helpful to obtain the actual throughput achieved which reveals the bandwidth usage efficiency. The higher the average throughput is, the better the bandwidth is utilized.

2.2.2.2 Delay (or Latency)

Delay, τ, sometimes refers to as end-to-end delay, is the time between the originating node sending a packet and that packet reaching the destination. It may vary dramatically because of long queue time or a congested network environment.

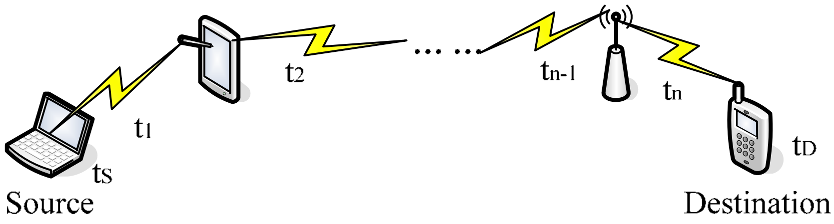


Figure 2.3 Delay components

As shown in Figure 2.3, delay is additive in the sense that it is built up over relay nodes

$$\tau = t_S + t_1 + t_2 + \ldots + t_{n-1} + t_n + t_D \quad (2.2)$$

where t_S and t_D denote processing time at the source and destination respectively. The buffering time of a packet is of great importance for delay. If the buffering time in an individual node is set to a higher value, it could imply that packets could stay in the buffer for a long period of time when link breakages occur which will may reduce the packet dropping rate [26]. In this case, the delay is higher. On the contrary, if the buffering time is shorter, the performance of delay will improve but the packet dropping rate will increase. Delay and packet delivery ratio are traded off in different applications.

Delay can be computed in multiple layers (e.g., application layer, transport layer network layer and link layer) and thus it is layer-dependent. For the sake of synchronization, round trip delay is used in some literature while others use single trip delay. In this thesis one-way delay is computed in the application layer by using a time stamp in the packet header

$$\tau = R_t - S_t \tag{2.3}$$

where R_t and S_t denote time at the source and destination for a given packet respectively, assuming suitably synchronized clocks in the transmitter and receiver. In some cases, excessive delay can render some time sensitive applications such as VoIP or online gaming unusable.

2.2.2.3 Jitter

Jitter was originally used in signal processing where it measures the deviation of some pulses in a digital signal and can be expressed in terms of phase, amplitude or width of the signal pulse. In the context of mobile ad hoc networks, the term jitter is defined as the average of difference between instantaneous delay and average delay [50]

$$\Delta\tau = \frac{\sum_{i=1}^{n} \left|(\tau_i - \tilde{\tau})\right|}{n} \tag{2.4}$$

where n denotes number of effective received data packets, τ_i symbolizes delays for different data unit and $\tilde{\tau}$ represents the average delay. It is reported that jitter can degrade live video quality nearly as much as packet loss rate [51].

2.2.2.4 Packet delivery ratio

The effective delivery ratio of data packets, α, is defined as:

$$\alpha = \frac{ENDP}{TNTP} \tag{2.5}$$

where *ENDP* and *TNTP* denote number of effectively received and total data packets respectively. Retransmission degrades the packet delivery ratio because it increases the denominator. A high packet delivery ratio is desirable, especially in MANETs, since the bandwidth available is limited for wireless links.

2.3 QoS routing in MANETs

The rapid growth of video in mobile traffic has resulted in a shift of research interests from best effort service to the provision of higher and better quality of service in MANETs. QoS routing algorithm design is challenging because it has to deal with unfavourable conditions such as time-dependent wireless links, dynamic topology and energy constraints. Considerable efforts have been devoted to this which leads to the emergence of a number of QoS routing techniques.

Generally speaking, two schemes, new protocol design and QoS-aware extension, are adopted to implement QoS routing. New protocol design refers to developing an algorithm with a new methodology while QoS-aware extension means combining QoS guarantee schemes with some well-studied protocols (e.g., DSDV, DSR and AODV).

2.3.1 New protocol design

Ad hoc QoS On-demand Routing (AQOR) [52] performs accurate admission control and reservation in an unsynchronized wireless environment to support QoS in terms of bandwidth and end-to-end delay. The destination is involved in the QoS violation detection to reduce the routing adjustment overhead. A temporary reservation scheme is developed to avoid routes that can’t meet QoS requirements. In some high mobility scenarios, the packet delivery ratio of AQOR can be as high as 98%. One problem of AQOR is its dependency on the reverse path for the route registration process, however the assumption of a bi-directional link may not be satisfied in some situations.

Unlike the resource reservation method in [52], Liao *et al.* [53] depend on tickets to search for multiple routes where certain bandwidth requirements are guaranteed in Multipath QoS Routing (MQR). One distinguishing characteristic of Liao's method is that tickets from the source can be partitioned into sub-tickets. This multi-path method doubles the route establishment success rate compared to Chen's single path method [54]. Overhead is incurred owing to the exchange of tickets and sub-tickets.

In Associativity-based Dynamic Source Routing (ADSR) [55], a metric called associativity is developed and used to search for paths satisfying QoS requirements. In ADSR the destination is responsible for computing a fitness function which takes hop count and route weight as parameters and decides the final route. Simulation results show that ADSR performs 20% better in respect of throughput compared to AODV and DSDV. Moreover, 2% and 3% more packets are delivered successfully for ADSR compared to AODV and DSDV respectively.

Kim *et al.* [56] present a signal-to-interference and bandwidth routing (SBR) which reserves bandwidth by allocating time slots. Besides addressing the bandwidth requirement, SBR also has an SIR (Signal-Interference-Ratio) constraint. If no single route satisfies both bandwidth and SIR requirements, SBR establishes multiple paths for a session. As multiple paths satisfy bandwidth and SIR demands simultaneously, arrival time and hop count are measured to decide the final route owing to the observation that less congested paths generally introduce smaller delays from the route reply packet and a smaller hop count implies a shorter route. SBR is a cross-layer protocol in the sense that it controls both time slot (network layer) and power (physical layer) assignment. The probability of call denials caused by lack of suitable paths is reduced by approximately 30% to 40% in SBR. However, it is quite difficult to find a reasonable SIR threshold because values that are too large will decrease the successful rate of route discovery and too small a value may result in poor quality link selection.

Sheng *et al.* [57] develop a routing protocol with QoS guarantees for ad hoc networks

(RQG) which tries to avoid hotspots. When the destination returns an RREP packet, the nodes within the path include their queue length information in the application layer. Multiple paths are employed to balance the traffic in the whole network and thus delay is minimized. The packet delivery ratio is improved by about 5% compared to standard DSR. However, the addition of queue length to the control packets leads to additional overhead.

Fan [58] proposes QoS routing using lower layer information in ad hoc networks (QLLI). MAC-layer delay, link reliability and residual bandwidth are considered in the route establishment process. The effect of this method is to lessen the probability of hotspots as well as unreliable links. By filtering out links that fail to satisfy bandwidth needs, QLLI finds the shortest path with the help of link weights. Fan concludes that the success ratio can approach the ideal exhaustive search algorithm by his method. One disadvantage of Fan's method is its requirement to update the state of paths. In addition, an evaluation of MAC-layer, link reliability and residual bandwidth needs to be implemented and stored in each node, which results in extra cost.

In [59], Venkatasubramanian *et al.* argue that the traffic should be balanced to avoid congestion and proposes a QoS-based Robust Multipath Routing (QRMR) to improve network capacity. In QRMR, the destination sends Route REply Packets (RREP) with information of cost such as link quality, channel quality and end-to-end delay. Upon receiving the RREPs, the source chooses the path with minimum cost. Simulation results in [59] show that packet delivery ratio for QRMR is improved by about 50% and delay is halved. However, Venkatasubramanian *et al.* fail to give detailed information on the channel quality and link quality estimation method used in their work.

2.3.2 QoS-aware extension

New algorithms for QoS provision in MANETs are surveyed in 2.3.1; this part focuses on QoS-aware extensions for the existing well-studied protocols.

2.3.2.1 AODV based extension

In [60], Li *et al.* propose an AODV based reactive spectrum assignment algorithm QOCWA which considers spectrum as continuous resource rather than discrete one. According to Li *et al.* the probability of contention as well as interference can be reduced through the creation of small bandwidth sub-channels and throughput may be enhanced when small parts of the spectrum are bundled together adaptively. The admission ratio is improved by 8% to 12% and the packet delivery ratio is almost doubled using this scheme. However, the assumption of multi-radio and multi-channel terminals incurs extra cost because nodes have to manage spectrum selection.

Espes *et al.* [61] propose a reactive TDMA-oriented algorithm DBCTO to support both delay and bandwidth metrics based on the observation that slot reservation only influences neighbours within two hops and the network throughput can be optimized by selecting paths with a lower number of neighbours. New fields such as bandwidth and delay requirements, number of neighbours, and time slot are added in the route request packet (RREQ). This algorithm is different from traditional source routing in the sense that not only the source but also intermediate nodes and destination have an impact on the final route selection.

A bandwidth reservation scheme is integrated into the traditional AODV protocol to produce QoS-AODV [62]. QoS-AODV, unlike other route discovery protocols that ignore the impact of the data link layer, incorporates slot scheduling information to ensure end-to-end bandwidth reservation in a TDMA network. Each MAC TDMA consists of a control phase and a data phase. Simulation results show that QoS-AODV doubles call acceptance ratio over standard AODV. Overhead is increased in QoS-AODV owing to the fact that routing table entries are created on a “per call ID” basis.

QAODV (QoS AODV) [63] designed by Shayesteh *et al.* also makes an extension to standard AODV. In addition to the number of hops, QAODV takes several other parameters such as the speed of the node, the battery power, the radio sensitivity in the receiver, the antenna gain, transmission range and bandwidth into consideration. A weight function which consists of a logical "AND" of different metrics is composed and used to decide the route. A gain of 15% for throughput is obtained at the cost of additional overhead in RREQ packets.

QAODV is further modified to IQAODV (Ad Hoc QoS Routing Protocol Based on Pertinence between Delay and Bandwidth) [64] by converting the bandwidth requirement to delay, based on the relationship between them. Two metrics, accumulated delay and the delay upper bound, are added into each routing entry to solve the problem that intermediate nodes in QAODV are not capable of sending an RREP packet. The packet delivery ratio and delay of QAODV are tripled and halved respectively by using IQAODV.

Agbaria *et al.* [65] present a dynamic Bandwidth Management (dBM) scheme for high mobility environments. In dBM, nodes broadcast bandwidth reservation requirements but that information is only limited to its two-hop neighbours. Delay is reduced in dBM. The work done by Cerda et al. [66] is quite similar to that of Agbaria's in the way that only 2-hop neighbours are concerned. However, the difference is that the later lacks the consideration of mobility.

2.3.2.2 DSR based extension

Geng *et al.* [67] developed the QoS-aware Multipath Routing (QAMR) Protocol based on local information analysis. In QAMR, nodes use the state of the MAC (either busy or idle) to estimate the available local bandwidth. Meanwhile two new metrics, node utilization factor and path congestion factor, are developed. The former describes the level of congestion while the latter depicts the highest node utilization level of the nodes on the path. When the destination receives RREQ packets, paths with a lower node utilization factor are included in the RREP packet. The path with the smallest path congestion factor is preferred by the source. QAMR increases packet delivery ratio by 47.9% and decreases delay by 51.3% compared to DSR. What's more, 15.1% reduction of energy is observed in QAMR. However, intermediate nodes are not allowed to reply to the RREQ packet which may extend the route discovery time and result in extra overhead.

In addition to QAMR, Geng *et al.* [68] also develop a partial bandwidth reservation (PBR) scheme for QoS support routing in mobile ad hoc networks. The bandwidth estimation algorithm of PBR is the same as that of QAMR. However, the intermediate nodes are able to filter out RREQ packets that do not satisfy the bandwidth constraint. The eligible intermediate nodes that have enough bandwidth are selected by the destination. PBR increases the network capacity by 100% compared to full bandwidth reservation schemes but maintains the same level of delay. However, the gain of network capacity is based on the cost of additional network overhead incurred by local bandwidth information maintenance in each node.

Like QAMR, BARP (Maximum Bandwidth Routing Protocol) also forbids intermediate nodes from replying to RREQ packets even if they know a route [69]. Instead, occupied time slots are attached to RREQ packets. The destination estimates the available bandwidth with the help of time slot assignment information from the RREQ packets and selects the path that has the maximum bandwidth from multiple routes. BARP increases throughput by about one third compared to standard DSR.

Although the efficiency of bandwidth usage is improved, the reliability of the selected path is not considered by BARP. Therefore, it is not suitable for scenarios where network topology changes dynamically. Instead, the MP-DSR algorithm [70], developed by Leung *et al.*, seeks to find a set of unicast routes that satisfy a minimum end-to-end reliability in a rapidly changing environment. End-to-end reliability refers to the probability of successful data delivery between two mobile nodes within a given period. It is distinct from the QoS metric packet delivery ratio in the way that the latter excludes repeated packets. RREQ packets are forwarded by intermediate nodes whose local reliability value exceeds the pre-defined threshold before it reaches the destination. A RREP packet, including the selection result by the destination, is transmitted via the reverse link. The source transmits data packets according to the selection information in the RREP packet. It is reported in [70] that the successful delivery ratio stays above 90% when node mobility increases from 0 m/s to 4 m/s.

2.3.2.3 TORA based extension

INORA combines INSIGNIA [71] and TORA to provide QoS support in MANETs. INSIGNIA is good at reserving and releasing resources, creating, breaking and recovering flows. The source initializes the route establishment process by propagating a RREQ packet which contains the bandwidth requirement. If an intermediate node has enough resource it will reply to the source and reserves corresponding resource. The process continues until a route satisfying the QoS requirements is obtained.

Rather than bandwidth reservation, delay is considered in Energy and Delay aware TORA (EDTORA) [72]. When the source activates a route discovery process, intermediate nodes examine the local energy values first. Only when the remaining energy is above a threshold, will a node estimate the delay and compare it with the delay constraint. In other words, only the nodes that satisfy both energy and delay requirements are selected. 20% more packets are successfully delivered by EDTORA compared to standard TORA.

2.3.2.4 OLSR based extension

Munaretto *et al.* [73] propose a link state routing protocol which extends standard OLSR to satisfy delay constraints. The creation time of a HELLO message is attached to this message. Upon receiving the HELLO message, the delay can be computed through a synchronized clock. Consequently, up to 18% of transmission time is saved by QOLSR compared with standard OLSR.

The assumption of synchronization in [73] is hard to realize in many mobile ad hoc networks. This constraint is relaxed in Kunavut's work of CIDQ [74] which seeks feasible routes by examining delay. A new metric called Connectivity Index (CI) is developed to encompass the capacity as well as connectivity of a link. Throughput is raised by 6.25% using this scheme compared to standard OLSR. A 6.13% enhancement in packet delivery ratio is also shown.

Table 2.2 Comparison of algorithms for QoS support

Protocol	QoS metric guaranteed	Strict QoS guarantee	Energy aware	Multipath	Cross-layer	Scheme
AQOR	TP, delay	No	No	No	No	Resource reservation
MQR	TP	No	No	Yes	No	Tickets
ADSR	TP, PDR	No	No	Yes	No	Function based
SBR	TP	No	No	Yes	Yes	TDMA
RQG	delay	No	No	Yes	Yes	Traffic balancing
QRLLI	PDR	No	No	No	Yes	Function based
QRMR	PDR	No	No	Yes	Yes	Traffic balancing
QOCWA	PDR	No	No	Yes	Yes	Channel division
DBCTO	TP	No	No	Yes	No	TDMA
QoS-AODV	TP	No	No	No	Yes	Resource reservation
QAODV	TP	No	No	No	Yes	Function based

Protocol	QoS metric guaranteed	Strict QoS guarantee	Energy aware	Multipath	Cross-layer	Scheme
IQAODV	PDR, delay	No	No	No	Yes	Function based
dBM	delay	No	No	No	No	Resource reservation
QAMR	PDR, delay	No	No	Yes	Yes	Function based
PBR	TP	No	No	No	No	Resource reservation
BARP	TP	No	No	No	No	TDMA
MPDSR	PDR	No	No	Yes	No	Function based
INORA	TP	No	No	No	No	Resource reservation
EDTORA	delay	No	Yes	No	No	Function based
QOLSR	delay	No	No	No	No	Function based
CIDQ	TP	No	No	No	No	Function based
* TP — throughput; PDR — packet delivery ratio						

Table 2.2 summarizes some properties of the algorithms reviewed above. As seen, 17 out of 21 protocols provide single QoS metric support while the remaining 4 algorithms support two QoS metrics. None of them support strict QoS guarantees due to dynamic topology and unpredictable links. Energy consumption is only considered in EDTORA although many nodes are battery powered. Less than half of the protocols depend on multipath routing and thus they may not support jitter sensitive applications for the reason that different routes incur different delays. Just over half of the designs adopt a layered philosophy which is the de facto architecture in conventional wired networks whereas others use cross-layer optimization.

Using a layered structure, designers can concentrate on a single layer without worrying about the effect of the rest of the stack. Despite successful application in wired networks, the layer structure creates some problems [75] because of hostile conditions such as dynamic link quality and node mobility in wireless environments. Some literature [75] has shown that gains can be achieved through interlayer information sharing. Therefore some protocol designers focus on cross-layer optimization over MANETs. In this thesis, a layered structure is adopted. Arguments in favour of this structure are that it is compatible with the current system and efforts can be concentrated at the network layer.

2.4 Issues in QoS support over MANETs

Several issues have to be considered for QoS support routing in MANETs.

2.4.1 NP-Complete problem

As shown in Table 2.2, the surveyed protocols support at most 2 QoS metrics for MANETs. However, support of more QoS metrics is required in many applications. It has been proved that providing at least two QoS metrics support in routing is a NP-complete problem [76]. An NP-complete problem can generally not be solved any more quickly than via an exhaustive search of the solution space which takes a long period of time. [77].

2.4.2 Application dependent nature of protocols in MANETs

Although much literature succeeds in providing support for one or two QoS metrics, they fail to evaluate the proposed method in all kinds of configurations. Table 2.3 summarizes performance results for some routing protocols over MANETs. As shown, the performance of the same protocol may vary dramatically with the variation of network configuration. The same conclusion is also obtained in [81].

The key reason for this phenomenon lies in the variability of design axioms. For example, DSDV depends on the HELLO messages to maintain the routing table rather than initiating a route request reactively as in DSR. Therefore, it is quite suitable for small size networks where the topology changes slowly. On the contrary, DSR adopts an on-demand mechanism which incurs less routing overhead and is more appropriate for a rapidly changing environment.

To design QoS provision routing and validate its effectiveness against other similar protocols with more than 2 metrics may take several years due to the NP-completeness of the multi-constraint problem and unfortunately this new algorithm is application dependent which means it only fits a given scenario. Thus, developing an all-round QoS support routing scheme for MANETs using this process is not practicable. Even if an all-round QoS routing were to be developed, it is still impossible to provide strict QoS guarantees due to the inherent characteristics of MANETs. Consequently, a best effort QoS support (BEQoS) model is proposed in this thesis in which alternative protocols are evaluated and ranked according to relative importance of QoS metrics. BEQoS model has two evaluation methods for different applications.

Table 2.3 Performance comparison

Protocol	**Metric**	**Results**	**Conditions**
AODV **DSR** **DSDV** **[78]**	PDR	AODV > DSR > DSDV	pause time ∈ [0, 200s]
	delay	DSDV<AODV<DSR	pause time ∈ [25s, 80s]
		DSDV<AODV<DSR	pause time ∈ [120s, 160s]
		DSR=DSDV<AODV	pause time ∈ [160s, 200s]
AODV **DSR** **OLSR** **[79]**	PDR	OLSR>AODV>DSR	node speed ∈ [0, 6 m/s]
		AODV>DSR >OLSR	node speed ∈ [6 m/s, 20 m/s]
	delay	AODV>DSR >OLSR	node speed ∈ [0, 6 m/s]
		DSR>AODV>OLSR	node speed ∈ [6 m/s, 20 m/s]
	PDR	AODV>DSR >OLSR	number of flows ∈ [0, 35]
		OLSR>AODV>DSR	number of flows ∈ [35, 100]
	delay	AODV>DSR >OLSR	number of flows ∈ [8, 15]

Protocol	Metric	Results	Conditions
		DSR>AODV>OLSR	number of flows ∈ [25, 100]
AODV DSR,TORA DSDV [80]	PDR	DSR>AODV>TORA>DSDV	pause time ∈ [0, 300s]
		DSR>AODV>DSDV>TORA	pause time ∈ [300s, 1000s]

2.5 Performance evaluation

There are two key factors for performance evaluation, metrics and techniques. Evaluation metrics are important as selections of different metrics may result in different conclusions.

2.5.1 Performance evaluation metrics

Routing metrics are important in the way that they have impact on both the complexity of path computation and the range of QoS requirements that can be supported [76]. Indeed, some tradeoffs between performance metrics have previously been reported.

(I) Throughput vs. Delay

It has been shown in [82] and [20] that capacity can be traded off with end-to-end delay in MANETs. If delay constraints are relaxed the capacity of the network can be increased by exploiting multiuser diversity. Neighbours of the source may cache the packets from a session and relay them to the destination when they move into transmission range [20]. At the other end of the spectrum, if multiple copies of a packet are forwarded on multiple paths, the destination will generally receive the packet with the shortest delay. The delay metric improves at the cost of network capacity utilization efficiency reduction [20]. One side-effect of such a scheme is a reduction in energy efficiency.

(II) Packet Delivery Ratio (PDR) vs. Capacity

In a similar way to the trade-off between delay and capacity, PDR can also be traded off against capacity as well as energy consumption. The probability of the destination receiving the packet from the source will be increased if redundancy is introduced by sending multiple copies of packets over different routes. However this scheme reduces the useful capacity of the network. Similarly, redundancy also increases the energy expended per packet.

Besides metrics such as delay, packet delivery ratio and throughput, energy cost is often selected during performance evaluation for MANETs due to limited energy supply in many mobile nodes. Energy consumption E_c is defined as

$$E_C = \frac{OEC}{ENDP} \tag{2.6}$$

where *OEC* and *ENDP* denote overall energy consumed and number of successfully received data packets respectively. Ideally, energy consumption should be balanced within the network in order to prolong the lifetime of the whole system.

2.5.2 Performance evaluation techniques

In addition to performance metrics, evaluation techniques are also of great importance. Generally speaking, there are three methods to evaluate the performance of a given scheme, namely practical implementation, mathematical derivation and simulation. Results achieved by practical implementation are credible but they are scenario related and can't be repeated. Mathematical derivation is comprehensive, but it is complicated and assumptions in the mathematical model deteriorate the credibility. Simulation offers the ability to evaluate multiple systems in a number of scenarios in a repeatable manner. However, just as with mathematical modelling, modelling assumptions may decrease the credibility of the results.

Performance evaluation of routing protocols in this thesis is based on simulation for the sake of convenience and credibility. For simulation, version 2.32 of the well-known open-source software NS-2 [83] is used. Mathematically, the QoS based performance evaluation oriented routing selection can be treated as a single-objective multi-attribute decision problem. The sole objective is to rank those alternatives and choose the best one according to the preference of QoS metrics. The QoS requirements are regarded as attributes, and the routing protocols are considered to be alternatives. There are several popular multi-attribute decision methods which are listed below.

2.5.2.1 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

(I) Principle

As the name indicates, the philosophy behind TOPSIS [84] is that the preferred alternative should be as close to the best solution as possible and as far away from the worst one as possible. The best solution is composed of the best performance values in all alternatives for each attribute. Similarly, the worst solution is a composite of the worst values. Euclidean distance is measured for each alternative and the one with the smallest value to best solution is desired. Generally, three steps are involved in the TOPSIS method:

(1) To compute the distance of each alternative from the ideal solution via $S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - a_{ij}^+)^2}$, where a_{ij}^+ denotes the ideal solution;

(2) To compute the distance of each alternative from the negative-ideal solution via $S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - a_{ij}^-)^2}$, where a_{ij}^- denotes the negative-ideal solution;

(3) Finally the relative closeness to the ideal solution is calculated through $C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-}$.

The larger C_i^+ is, the better.

(II) Applications

Wang *et al.* [85] rely on TOPSIS to help the Air Force Academy in Taiwan to choose optimal initial training aircraft. It is demonstrated by a case study which contains 16 evaluation criteria, seven initial propeller-driven training aircraft assessed by 15 evaluators from the Taiwan Air Force Academy. Li *et al.* [86] use TOPSIS in bid evaluations of manufacturing enterprises and it is reported that TOPSIS is a good method in manufacture enterprise invitation and submission of bids.

TOPSIS is also applied in the field of telecommunications. [87] describes an interface selection problem with the help of TOPSIS. Selection criteria in [87] are price, bandwidth, signal-noise-ratio (SNR), sojourn time, and battery consumption.

2.5.2.2 Multi-attribute Utility Analysis (MAUA)

(I) Principle

MAUA [88] involves four steps. To begin with, performance metrics for a particular application should be identified. Secondly, pair-wise comparisons between two alternatives are performed to measure the utility. Thirdly, the utility function has to be determined. Finally, the utility values are obtained for alternatives with respect to the performance metrics.

(II) Applications

Lewis *et al.* use MAUA to evaluate the goals and services of a state vocational rehabilitation (VR) agency which is undergoing a comprehensive strategic planning process and had adopted the MAUA model to support aspects of its planning [89]. [90] constructs an index of environmental impact for an electric utility based on MAUA.

In the area of telecommunication, Tran *et al.* [91] propose a utility oriented interface selection scheme to handle such problems. There are three considerations of Tran's method: application requirements, terminal characteristics and network attributes such as delay and cost. The key methodology is to develop a metric named distance to the ideal alternative (DiA) to rank the interfaces available according to utility functions. To achieve this, four steps are followed:

(4) Application utility function construction: this function is defined as a function of the available bandwidth.
(5) Battery consumption function calculation: since mobile devices are battery powered, energy is a critical factor. The battery consumption function is the multiplicative result of energy consumption per bit and data volume transferred.
(6) Interface utility function determination: this consists of two parts. The first one is the multiplicative result of U_{ij} which denotes the application satisfaction level of interface *j* over interface *i*. The second part is Q_{ij} symbolizing the battery consumption level of interface *j* over interface *i*.
(7) DiA computation and ranking: once the utility functions of all interfaces are obtained, the positive ideal interface (PiI) is constructed. The optimal interface is the one which has the shortest distance to PiI.

A similar utility based method is also employed in [92] which combines MAUA with TOPSIS. The first step of this method is the same as that of Tran's. Instead of energy consumption, a new metric, termed access delay, which represents the time consumed to obtain authority and authentication of users is included.

2.5.2.3 ELimination Et Choix Traduisant la Réalité (ELECTRE)

(I) Principle

ELECTRE [93], originally proposed by Bernard Roy *et al.*, has evolved since its first application in 1965. Two concepts, concordance and discordance, are developed to describe the level of satisfaction and dissatisfaction. The first step of ELECTRE is to compare alternatives. Let network 1 and 2 be two alternatives, the concordance set CS_{12} is

$$CS_{12} = \{j : (A_{1i} \geq A_{2i})\} \quad (2.7)$$

which means network 1 is preferred over network 2 when criterion i is being considered. Similarly, the discordance set DS_{12} for criterion j is

$$DS_{12} = \{j : (A_{1j} < A_{2j})\} \quad (2.8)$$

Then the concordance matrix C_{dom} is calculated as follows:

$$\begin{aligned} (C_{dom})_{kl} &= 1 \quad if \quad C_{kl} \geq C_{threshold} \\ (C_{dom})_{kl} &= 0 \quad if \quad C_{kl} < C_{threshold} \end{aligned} \quad (2.9)$$

where $C_{threshold}$ is the threshold for concordance. Similarly, the discordance matrix is

$$\begin{aligned} (D_{dom})_{kl} &= 1 \quad if \quad D_{kl} \geq D_{threshold} \\ (D_{dom})_{kl} &= 0 \quad if \quad D_{kl} < D_{threshold} \end{aligned} \quad (2.10)$$

The aggregate dominance matrix A_{dom} is

$$(A_{dom})_{kl} = (C_{dom})_{kl} * (D_{dom})_{kl} \quad (2.11)$$

If $(A_{com})_{12} = 1$, it indicates that network 1 is preferred.

(II) Applications

ELECTRE is commonly used in areas such as energy and environment protection [94] [100], finance [101]-[103]and project selection [104] [105].

Bari *et al.* [106] apply ELECTRE in access technology selection. Metrics like cost per byte, allowed bandwidth, total bandwidth, link utilization, delay, and jitter as well as packet loss are chosen to formulate the attribute vector for the ELECTRE method. Some modifications of standard ELECTRE are made in [106] to allow for non-monotonic utility in metrics. The two metrics, concordance and discordance, that denote the satisfaction and dissatisfaction of one alternative over another one respectively, are then developed.

2.5.2.4 Simple additive Weighting (SAW)

(I) Principle

SAW, which is also known as weighted linear combination or scoring method, uses average weights to compute a score for each alternative. The score is the multiplicative result of scaled value for given alternatives under certain criteria with the weight of criteria. Three steps are included:

(1) Construction of a pair-wise matrix for criteria with respect to the objective;
(2) Construction of a decision matrix covering alternatives and criteria;
(3) Aggregation of criteria weights and alternative weights for a given criteria.

(II) Applications

SAW is applied in a variety of fields such as economics [107], location selection [108] and the environment [109]. In addition to TOPSIS, SAW is also used in [110].

2.5.2.5 Grey Relational Analysis (GRA)

(I) Principle

GRA defines situations with two extremes; black, which refers to no information known, and white which means perfect information is available. The situation in real world problems lies between those two extremes, and classed as grey. GRA doesn’t attempt to offer the best answer rather it provides technique to determine a good solution. Six steps are required to implement GRA:

(1) Classifying the elements as one of three classes: larger-the-better, smaller-the-better, and nominal-the-best;
(2) Defining the nominal value, as well as lower and upper bounds of elements;
(3) Normalizing individual entities;
(4) Defining the ideal elements;
(5) Calculating the Grey relational coefficient (GRC);
(6) Selecting the alternative with the largest GRC.

(II) Applications

GRA is widely adopted in project selection [111] and economics [112].

Two wireless networks are compared and evaluated with GRA by Song *et al.* in [113]. The metrics under considerations include throughput, timeliness which has three sub-metrics delay, response time and jitter, reliability which is divided further into bit error rate, burst error and average number of retransmission per packet, security and cost. Two alternative networks evaluated by Song *et al*. are UMTS (Universal Mobile Telecommunications System) and WLAN (Wireless Local Area Network). In [113], UMTS is always available during the simulation. Once the received signal strength of a WLAN exceeds a threshold and lasts for a period of time, an agent called the network selector begins to collect relevant information, evaluate alternatives and finally select the optimal network according to the objective. Four cases are studied to reveal the efficiency of the proposed method.

GRA is also applied in network evaluation and selection in [114] which compares two alternatives GPRS and WLAN. Parameters such as delay, jitter, information loss and error are considered.

2.5.2.6 Analytic Hierarchy Process (AHP)

(I) Principle

Analytic Hierarchy Process (AHP) [115] was first introduced by Saaty in 1970s and it has seen wide application in the past four decades. AHP first decomposes the decision problem into a hierarchy composed of an objective layer, a criteria layer and an alternative layer so that a hard problem can be more easily understandable. Once the hierarchy is built, the decision makers compare elements in a pair-wise fashion with predefined rules based on which the comparison matrices are obtained. Weights or priorities for criteria and alternatives are computed and aggregated to achieve the final synthetic weights for alternatives. The alternative with the biggest value of weight or priority is considered to be the optimal one among alternatives. Indeed, the aggregating algorithm is a kind of utility function.

(II) Applications

The application fields of AHP include environment problems [116] [117], the manufacturing sector [118] [119], logistics [120] [121], etc.

Ai *et al.* [122] address the network selection problem by fuzzifying standard AHP and integrating entropy theory. Also, a Service Level Agreement (SLA) management model is applied. Three steps are required:

(1) SLA establishment: This step includes two sub-steps: SLA template customization, in which users complete an SLA template to express the expected service, acceptable cost, responsibilities and rights, and SLA negotiation where the operator checks the user requirements and money paid and initializes re-customization when necessary.
(2) QoE (Quality of Experience) management: This step controls the quality of service in the SLA which includes QoE mapping, Network selection, QoE configuration and QoE adaption.

(3) SLA monitoring: Addresses QoE satisfaction level and reports QoE measurement realized to a specific place.

Operator reputation, user experience score, loss, delay, jitter, rate, throughput, cell radius and unit price are chosen as criteria.

Both [113] and [114] have applied AHP for network selection. The main difference is that the former uses AHP and GRA as two separated methods while the later integrates AHP into GRA.

Table 2.4 Comparison of multi-attribute decision methods

method	distance to ideal or negative-ideal solution	pair-wise comparison	scoring	Method to derive weights for criteria
TOPSIS	Yes	No	No	No
MAUA	No	Yes	No	Yes
ELECTRE	No	Yes	No	No
SAW	No	No	Yes	No
GRA	Yes	No	No	No
AHP	No	Yes	No	Yes

Table 2.4 summarizes characteristics of the six multi-attribute decision methods described above. As shown, the distance of one alternative to the ideal or negative-ideal solutions is used to obtain the ranking results in both TOPSIS and GRA. Only SAW uses a scoring method to measure the performance of an alternative. MAUA and AHP are able to derive weights for criteria. In this thesis, four methods, TOPSIS, SAW, GRA and AHP are used for comparison.

2.6 Summary

MANETs have some unique properties that are different from traditional wired networks, leading to difficulties in QoS support over MANETs. Due to the rising popularity of real-time applications, research interest has shifted from best effort to QoS support, resulting in several QoS support algorithms. However, those proposed protocols provide support for at most two QoS metrics and strict guarantees can not be given. Developing an algorithm with at least two QoS constraints is an NP-complete problem, and is only suitable for a given scenario. Based on these two findings, a best effort QoS support (BEQoS) model is introduced which evaluates and ranks protocols according to the relative importance of multiple QoS metrics. Several evaluation methods are surveyed finally in this chapter which will be considered in chapter 4.

Chapter 3 Simulation

As stated in the last chapter, simulation results are used as empirical knowledge based on which alternatives are evaluated in this thesis. This chapter introduces the simulation background and outlines some simulation results that will be used as empirical knowledge in the following chapters. It is organized as follows. The first section deals with simulation software selection. Section 3.2 describes the simulation scenario. Section 3.3 proposes a new implementation of the propagation model and modifies the adopted simulation tool. Section 3.4 presents the configuration for the simulations in this thesis. Section 3.5 presents the results as well as analysis. The final section summarizes this chapter.

3.1 Simulation software selection

To date, a number of simulation tools (e.g., NS-2 [123], GloMoSim [124], OPNET [125], QualNet [126] and MATLAB [127]) have been developed for wireless and ad hoc network simulations.

GloMoSim is a free simulation tool that depends on a discrete event mechanism. It has some good features such as modular design as well as the ability to scale up [128]. However, the protocol stack of GloMoSim is relatively simple and some well-known routing protocols such as TORA and OLSR are not included.

QualNet, which is commercial simulation tool, extends the GloMoSim in terms of protocol stacks and it provides a graphical user interface. It inherits the scalability of GloMoSim and thus is able to support large networks (e.g., 2500 nodes) [128].

OPNET (Optimized Network Engineering Tools) is a commercial simulator with a graphical user interface. It is well-organized in that many components such as mobility patterns, propagation models, MAC layer protocols and many routing protocols (e.g., AODV, DSDV) are already included.

NS-2 (Network Simulator version 2) is the most popular free simulation tool used in the field of mobile ad hoc networks [130]. It is equipped with lots of protocols and models. In addition, there is substantial technical support available in the open source community. NS-2 is split into the OTCL language and the C++ language. The former makes objects configuration easier while the latter closely mirrors the corresponding objects in OTCL efficiently.

MATLAB (MATrix LABoratory) creates a numerical computing environment that enables users to perform intensive tasks faster than traditional programming. It has some toolboxes for telecommunications, but these are limited in scope.

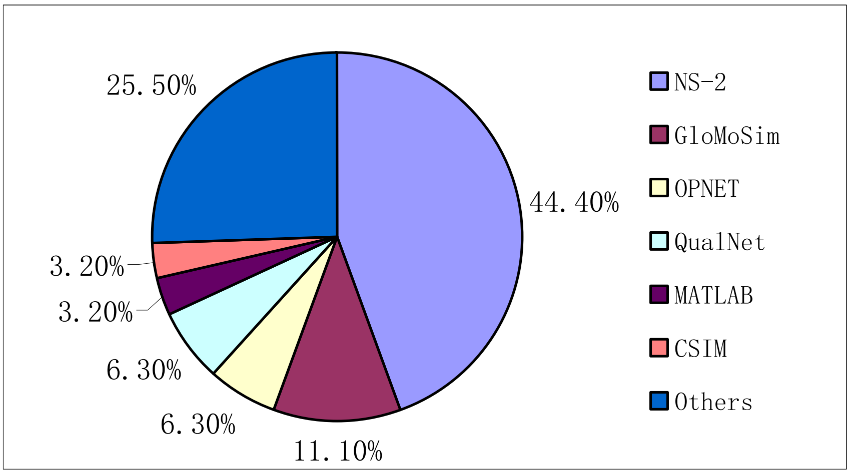


Figure 3.1: Simulation software usage in MobiHoc 2000-2004 [130]

A survey of simulation tools applied from 2000 to 2004, presented in the proceedings of ACM International Symposium on Mobile Ad Hoc Networking and Computing, is shown in Figure 3.1 [130]. It is observed that 44% of those papers adopt NS-2. In addition to the flexibility as well as convenience, the open source property also contributes to the success of NS-2. The role for NS-2 is so important in the research community of mobile ad hoc networks that it has become the de-facto reference simulator [128]. Since only a small network (30 nodes) is simulated in this thesis, the problem of scalability for NS-2 can be ignored. Therefore NS-2 is applied in this thesis.

3.2 Simulation scenario

The network performance of several mobile terminals (MTs) in a classroom building is studied in this thesis. As shown in Figure 3.2, nodes are assumed to share a common access point to access the Internet. The mobility speed is uniformly distributed between 0 and 1.5 m/s, simulating the movement of students and staff. Since the ORiNOCO11b wireless card is used for simulation parameters in some literature [130]–[132], parameters are set to match it and the modulation scheme of CCK11 (11Mbps) for the close range environment. The average transmission range of ORiNOCO11b card in a close-in environment is 25 m [133]. The transmission power is assumed to be 31 mW and the frequency is 2.472 GHz.

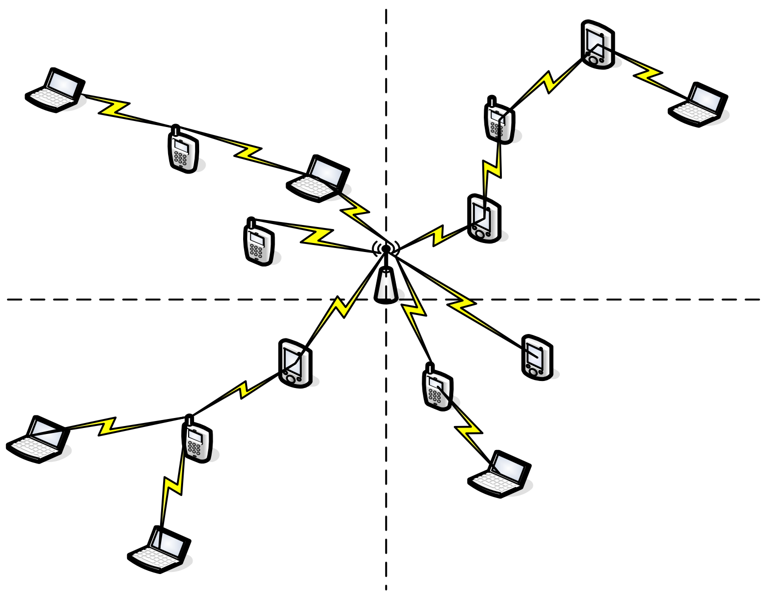


Figure 3.2 Simulation scenario

3.3 Simulator modifications

The version of NS-2 used in this thesis is NS-2.32, being the most recent at the time of the simulation work being carried out. However, some modules in this version are inaccurate, and have been amended as indicated in this section.

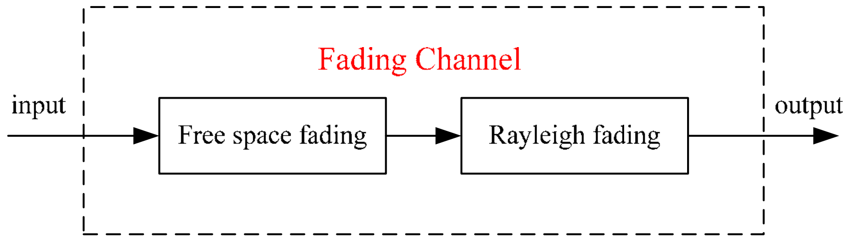
3.3.1 Propagation model

The electromagnetic propagation model has a significant impact on the measured wireless network performance [134] [135]. In reality, the received signal strength depends on a number of parameters due to various factors (e.g., reflection, refraction and scatting). Some of them, like the distance between sender and receiver or the utilized frequency are easy to realize within simulators whereas others must be defined as random functions or constant factors, such as interference or fading effects.

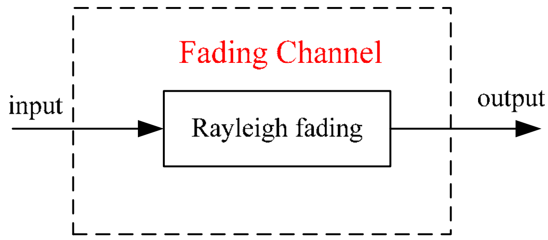
Ideally, propagation models should simplify calculations and thus reduce the required computation to the minimum in order to enable simulations to complete within an acceptable amount of time. The NS-2.32 simulator implements three basic propagation models, a free space (FS) model, a two ray ground (TRG) model and a shadowing model.

Rayleigh fading is viewed as a reasonable model for tropospheric and ionospheric signal propagation as well as the effect of heavily built-up urban environments on radio signals when there is no dominant propagation along a line of sight between the transmitter and receiver [136][137]. In campus buildings, MTs and access point are likely to be separated by objects such as walls and desks which attenuate, reflect, refract and diffract the signal in a classroom building. Consequently, it may be difficult to find a dominant line of sight between the transmitter and receiver in some applications. All three models available in NS-2.32 are considered inadequate for this type of environment. Therefore, a more appropriate propagation model Rayleigh fading model is implemented.

Wang [138] implements a Rayleigh fading model by adding code in the function of WirelessPhy::sendUp (Packet *p) and shows the difference before and after considering Rayleigh fading. Unfortunately, in Wang's implementation as shown in Figure 3.3 (a), the signal has to experience free spacing fading before it enters the Rayleigh fading channel and thereby it is not accurate. Rather than Wang's model, a separate Rayleigh fading model is proposed in this thesis in Figure 3.3 (b) and details regarding the new model are included in appendix A.



(a) Wang's Rayleigh fading model



(b) Rayleigh fading model in this thesis

Figure 3.3 Comparison of two Rayleigh fading model

3.3.2 Packet dropping model

In NS-2.32 when a packet reaches the MAC layer, a dropping model is utilized to determine whether this packet is correctly received or dropped.

3.3.2.1 Packet dropping model in NS-2.32

Figure 3.4 describes the packet reception process of NS-2.32 in the MAC layer. As shown, when a packet reaches a node, the signal strength P_r is estimated first. As long as P_r exceeds the Carrier Sensing Threshold (*CSThresh_*), it is then compared with the packet Receiving Threshold (*RXThresh_*). If P_r falls between *RXThresh_* and *CSThresh_*, this packet is discarded. In case P_r is larger than *RXThresh_* and there is only one packet during the reception period, this packet is tagged as successfully received. When multiple packets arrive simultaneously during the receiving period,

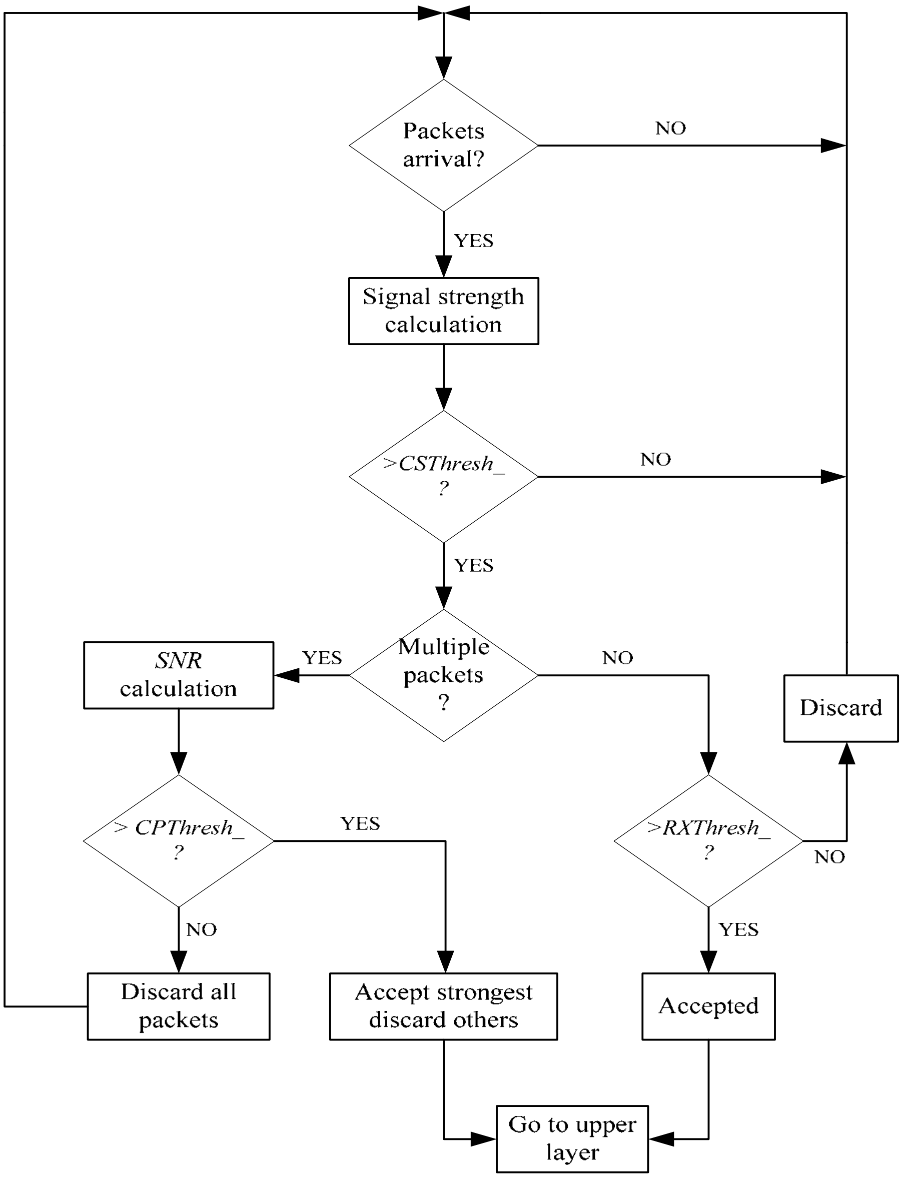


Figure 3.4 Flow chart of packet reception process in MAC layer

the packet with the largest signal strength is regarded as the signal whereas other packets are considered to be interference. The signal to interference ratio (SIR) is computed via

$$SIR = \frac{P_r(m)}{\sum P_r(i)} \quad i = 1, 2, ..., n \quad i \neq m \tag{3.1}$$

where $P_r(i)$ denotes the signal strength of $i^{'th}$ packet, $P_r(m)$ denotes the signal strength of $m^{'th}$ packet that has the maximum signal strength of all the n packets during the reception period. A noise term is not included in the formula (3.1) as this is ignored in NS-2.32.

Only if *SIR* exceeds *CPThresh_* will the strongest packet be correctly received, or it is ignored. All other packets that arrive simultaneously at the receiving node will be dropped. To conclude, NS-2.32 uses three thresholds to determine whether a packet is accepted in the MAC layer.

The three thresholds method is easily implemented and requires a small amount of time to determine whether one packet is received. However, there are several factors that are not considered in this model. To begin with, the background noise of the hardware is neglected. To determine the signal to interference and noise ratio (SINR), formula (3.1) should be modified to

$$SINR = \frac{P_r(m)}{P_{noise} + \sum P_r(i)} \quad i = 1, 2, ..., n \quad i \neq m \tag{3.2}$$

where P_{noise} denotes the power of noise.

What's more, the modulation schemes in each packet are not considered. For example in 802.11b the packet header is modulated with BPSK while the payload may be modulated with BPSK, QPSK, CCK 5.5 or CCK 11. Different modulations have different levels of noise immunity which may affect the packet dropping rate [133].

Last, but not least, NS-2.32 ignores the impact of packet structure. In most cases, information concerning the data payload (e.g., packet length) is stored in the packet header in NS-2.32. This is reasonable because it is pointless to carry data around in a non-real-time simulation [139]. However, the packet dropping scheme should take the length of the packet into account because it is strongly related to packet error rate which indicates the probability of dropping packets.

3.3.2.2 Proposed packet dropping model

Due to the disadvantages describe above, a new packet dropping model which is based on the packet error rate is proposed in this thesis. The proposed model considers noise level, and modulation scheme as well as packet length.

(1) Estimation of noise level

By definition, *CSThresh_* is the carrier sense threshold and therefore it should be identical to the receiver sensitivity of the hardware. As stated earlier, parameters from the ORiNOCO11b card are used and the values of *CSThresh_* in this thesis are listed in Table 3.1

Table 3.1 CSThresh_ for different modulation scheme

Modulation scheme	**BPSK**	**QPSK**	**CCK 5.5**	**CCK11**
Tx speed (Mbps)	1	2	5.5	11
CSThresh_ (dBm)	-94	-91	-87	-82

In the case that the signal strength of a packet exceeds the *CSThresh_*, indicating that the packet can be sensed by the receiver, the SINR is computed. If only one packet arrives during the receiving period, the SNR_1 can be computed as

$$SINR_1 = \frac{P_r}{P_{noise}} \tag{3.3}$$

P_{noise} can be estimated as 10 dBm below the receiver sensitivity in a practical system [133] and the values of P_{noise} are listed in Table 3.2. As long as multiple packets arrive simultaneously, the SINR is computed using formula (3.2).

Table 3.2 Power of noise immunity for different modulation scheme

Modulation scheme	BPSK	QPSK	CCK 5.5	CCK11
Rx sensitivity_ (dBm)	-94	-91	-87	-82
Noise immunity (dBm)	-104	-101	-97	-92

Given an SINR, the bit error rate (BER) can be derived theoretically [140] or obtained through empirical curves measured for a particular product [141]. Without loss of generality, the former method is employed in this thesis.

(2) Considerations for packet structure

The next step of the proposed model is to calculate the packet error rate (PER) which determines the probability of erroneous packets. As well as BER, packet structure also affects the value of PER. Packet structure refers to packet length and composition of the packet. Figure 3.5 depicts the packet structure of 802.11b which is used as a MAC layer in this thesis. As seen, 24 bytes of MAC header and 4 bytes of Frame Control Sequence (FCS) are attached to the packet in the MAC layer. In addition, the Physical Layer Convergence Protocol (PLCP) header and preamble, which are 18 bytes and 6 bytes respectively, are also attached in the physical layer. In 802.11b, BPSK modulation is used for the PLCP header and preamble frame. Therefore

$$PER = 1 - (1 - BER_{BPSK}^{8\times 24})(1 - BER_{Modulation}^{8\times(28+L)}) \tag{3.4}$$

where $BER_{BPSK}^{8\times 24}$ denotes error rate for the PLCP header and preamble of BPSK modulation and $BER_{modulation}^{8\times(28+L)}$ symbolizes the BER for a particular modulation scheme (i.e., QPSK, CCK) where L symbolizes the payload frame length in bytes. Finally packets are dropped according to the PER.

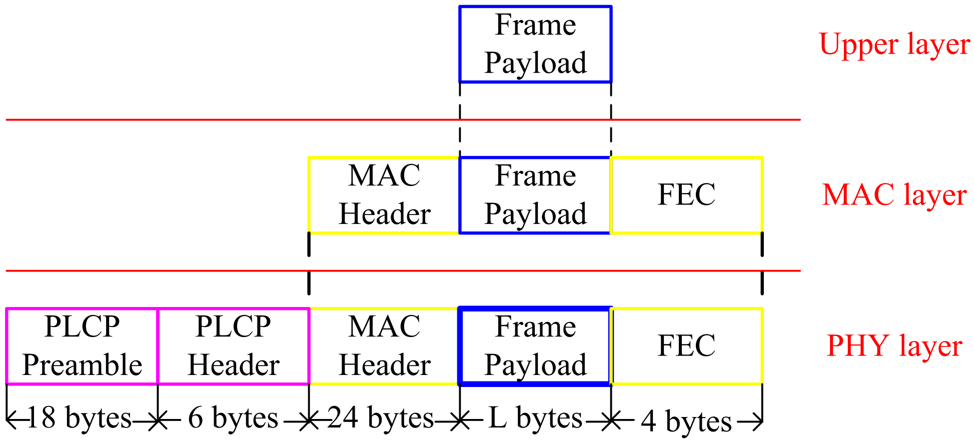


Figure 3.5 Packet structure of 802.11b

Compared to the original threshold model in NS-2.32, noise, modulation schemes and packet structure are all considered and therefore the quality of the packet dropping model is improved.

3.4 Simulation configuration

In addition to more accurate simulation models, simulation parameter configuration is also critical to avoid unbiased results.

3.4.1 Node mobility model

Various mobility models have been proposed, and can be divided into two categories, the entity model (e.g. Random Walk Mobility model, Random Waypoint model, Gauss-Markov mobility model) and the group model (e.g. exponential correlated random mobility model, Nomadic community mobility model, reference point group mobility model) to simulate the movement of MTs in the real world [142]. The former reflects the behaviour of individuals whereas the latter represents the group mobility characteristics. The entity model is adopted when only the individual terminal performance is of concern. One of the entity models, the random waypoint model (RWP), which has two variants (the random walk model and the random direction model), is regarded as a benchmark because of its simplicity and availability in a lot of simulations.

As shown in Figure 3.2, a mobile node in a classroom building moves with a random speed toward a destination and waits for a period time before moving again. This pattern can be easily simulated by the random waypoint model as described in [143] and therefore RWP is adopted.

3.4.2 Node initial position

As pointed out by J. Yoon *et al.* [144], network performance may be substantially different due to different configuration of node initial position, termed as initial position bias. The common solution is to discard the first section of the recorded data. William Navidi [145] gives two drawbacks, inefficiency and inaccuracy, concerning this method. By inefficiency, it means part of the data obtained in [144] will be discarded. By inaccuracy, it refers to difficulty in identifying the length of data that should be neglected. In the same paper, William Navidi proposes and verified a stationary distribution for location, speed, and pause time for the random waypoint mobility model. A step-by-step summary of this procedure is given in appendix B.

3.4.3 Topology

According to D. Kotz *et al.* [146], the mobility diameter in the campus is less than 50 m. For simplicity but without loss of generality, the width and length of four blocks in Figure 3.2 are all configured to be 50 m and a node moves within a block. For the sake of coverage, access points tend to be installed in the centre of a building thus the rectangular topology is 100 m × 100 m.

3.4.4 Number of nodes

According to [147], number of nodes in the network N is

$$N = N_n \times \frac{w_t \times l_t}{\pi \times r^2} \tag{3.5}$$

where w_t and l_t denote width and length of the topology respectively, N_n and r denote the number of neighbours and transmission range respectively. L. Kleinrock *et al*. [148] point out that 6 neighbours is the optimal value and if the number of neighbours is less than 6, it will cause drastic reduction in capacity of the network whereas exceeding 6 leads to gradual degradation. [149] has a similar conclusion. Consequently, the number of neighbours is configured to be 6. Through formula (3.5), the number of nodes to achieve this can be obtained (32 nodes).

3.4.5 Traffic

A survey conducted by D. Kotz *et al.* [150] found that TCP traffic accounts for a dominant 97.5% of all traffic in terms of bytes. Consequently, TCP is a used in this thesis as a transmission layer protocol.

K. Thompson *et al.* [151] point out that packet size peaks at the common sizes of 40 bytes, 552 bytes, 576 bytes and 1500 bytes. Almost 75% of the packets are smaller than the typical TCP MSS of 552 bytes. Nearly half of the packets are 40 to 44 bytes in length, corresponding to control packets. In this thesis, the data packet size is configured to be 552 bytes, including packet header and the volume of a TCP acknowledgement is 40 bytes which is similar to the result in [151].

Figure 3.6 describes the assumed traffic variation in the morning in a classroom building in this thesis. As seen, traffic volume is small (2 streams) at the beginning of the day and increases when students begins to enter the building, peaking at the time of 9:30-11:30. As lunch time arrives, the number of streams drops. The transmission interval of traffic is uniformly distributed between 0.5 and 10 on a per-node basis.

3.4.6 Summary of other simulation parameters

Hundreds of configurable variables are used during NS-2.32 aided simulations to support various requirements. A summary of the key simulation parameters adopted in this thesis is summarized in Table 3.3. Default values are assumed for other variables except where specifically mentioned.

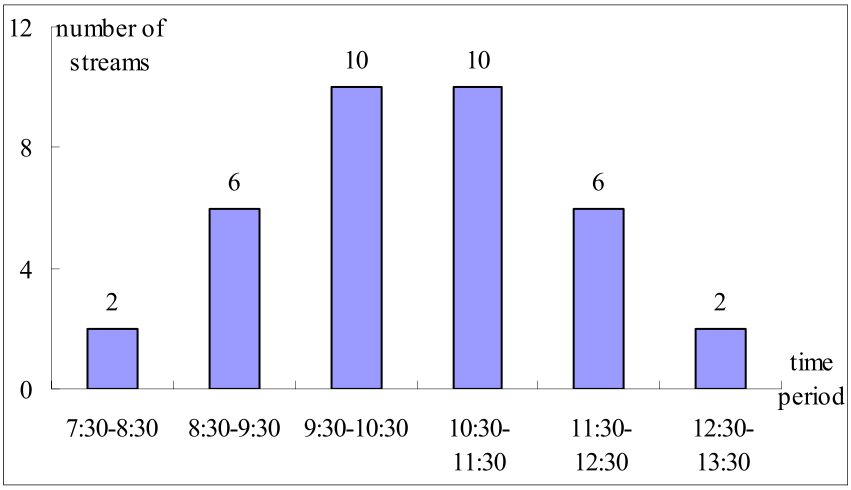


Figure 3.6 Traffic variation in the morning

3.4.7 Data collection

The simulation time lasts for 3000s and for each measure, 50 independent simulation runs are carried out and the final results are averaged. Four QoS metrics (1) Packet delivery ratio; (2) delay; (3) jitter; and (4) throughput and one performance metric, energy cost, are studied.

Table 3.3 Simulation parameters

Parameter	**Description**
Simulation time	3000 s
Number of independent simulation run	50
Number of nodes	32
Node mobility patter	Random WayPoint model
Mobility speed	Uniformly distributed [0, 1.5] m/s
Topology	100 m × 100 m
Propagation model	Rayleigh fading
Transmission range	25 m
Transmission power	31 mW
Frequency	2.472 GHz
MAC layer protocol	802.11b
Modulation scheme	CCK11 (11Mbps)
Packet dropping model	Packet error rate based model
Routing Protocol	DSDV and DSR
Transmission layer protocol	TCP
Number of streams	2,6,10
Interval between packets	Uniformly distributed [0.5, 10] s
Queue length	100 packets

3.5 Simulation results and analysis

Simulations are performed via NS-2.32 and the results are collected as follows.

3.5.1 Packet Delivery Ratio

As shown in Figure 3.7, DSR outperforms DSDV for all three flow loads. The difference of average packet delivery ratio between DSDV and DSR is marginal (4.4%) when the network has 2 streams. However, as the number of flows increases to 6, the difference expands to 15.9% which is quite large. Packet delivery ratio continues to decrease as the number of flows goes up to 10. Three factors contribute to the success of DSR. To begin with, DSR initiates the route discovery mechanism only when necessary, avoiding the use of stale routes. Secondly, if a link breaks down in the data transmission process, the upstream node may buffer the lost packets and activate the local link repair mechanism which increases the number of data packets that are able to be delivered. Last, but not least, DSDV broadcasts route information packets periodically and those packets may collide with data packets.

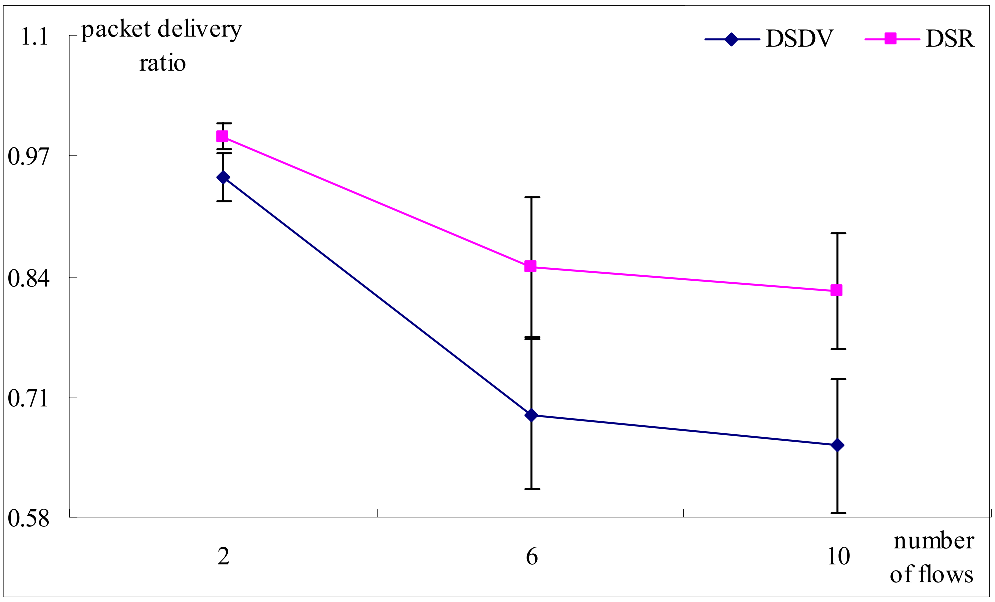


Figure 3.7 Packet delivery ratio

3.5.2 Delay

Despite better performance of DSR in terms of packet delivery ratio, DSDV outperforms DSR in delay as shown in Figure 3.8.

The average delay for DSDV is 1.98 ms in the case of 2 traffic flows and it almost doubles when number of flows increases to 6. The delay for DSDV remains constant when more traffic is added into the network. For DSR, the delay continues to increase as the number of streams goes up to 10. The key reason for this is the proactive nature of DSDV. DSDV updates routing tables according to periodic information received and thus can establish route quickly. Instead, DSR initiates a route discovery process on demand which takes more time.

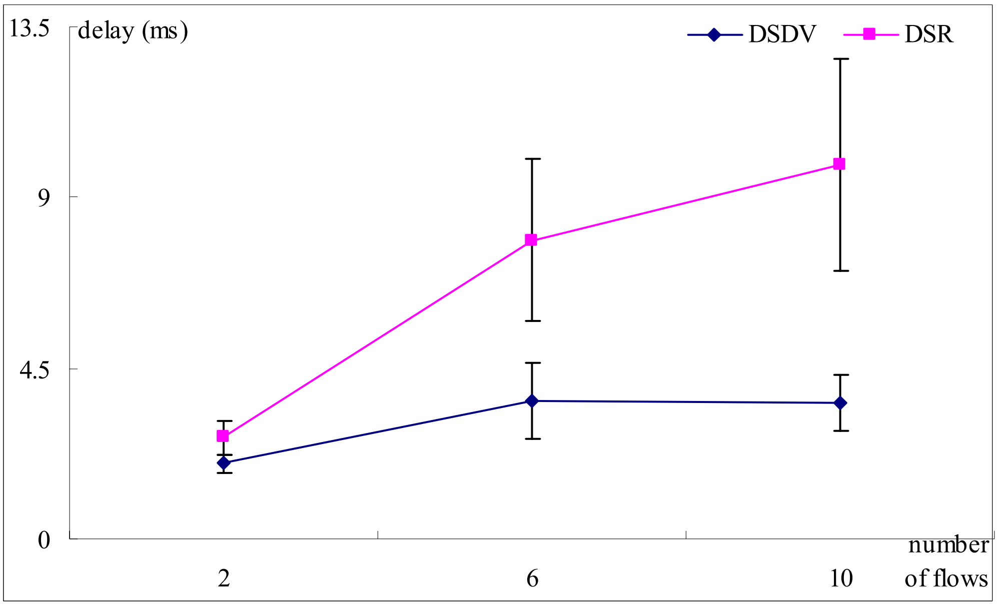


Figure 3.8 Average delay

3.5.3 Jitter

Figure 3.9 shows the averaged jitter results. Similar to delay, DSDV has a better performance in terms of jitter. The jitter for DSDV goes up as number of flows increases from 2 to 6 and stays stable if more traffic is introduced. As the number of streams is small, the source is able to re-establish a route when the previous connection breaks and therefore the jitter is small. However, with the increase of traffic, the network becomes busier, therefore more time is required to find a new route in case of route break.

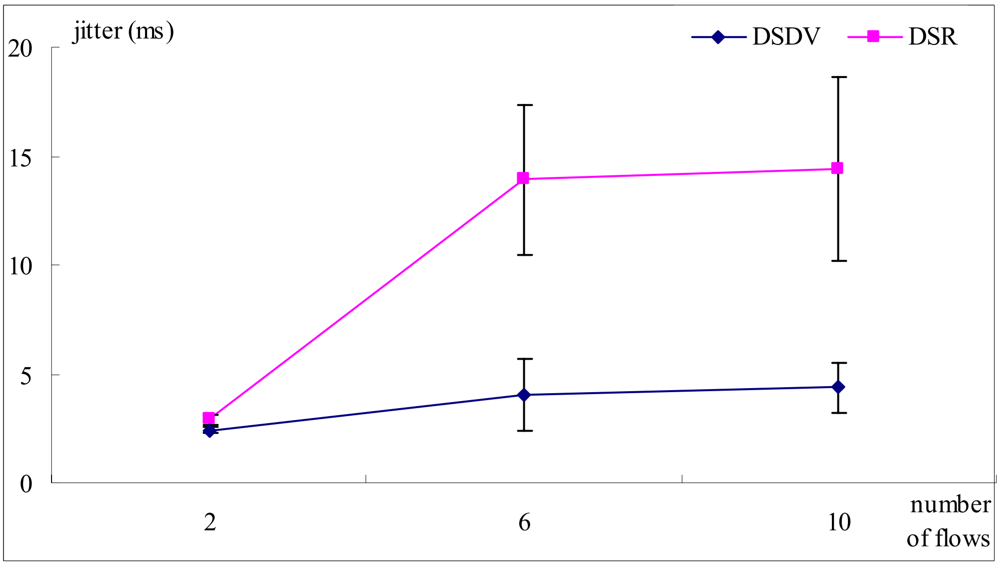


Figure 3.9 Average jitter

3.5.4 Throughput

As shown in Figure 3.10, DSDV is on average 9% better than DSR in terms of average throughput. Since DSDV broadcasts route information periodically, the probability of finding a shorter route for DSDV is higher than that of DSR.

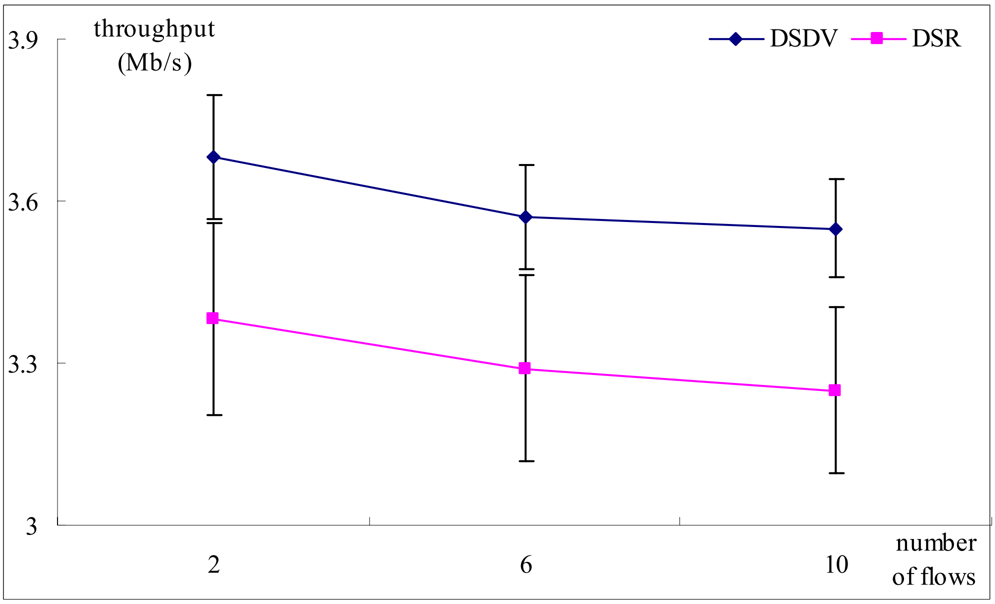


Figure 3.10 Average throughput

3.5.5 Average Energy Consumption

Figure 3.11 describes the average energy cost per packet for both DSDV and DSR. It is observed that DSDV consumes more energy than DSR and the energy consumption for both DSDV and DSR decreases as more traffic is added.

DSDV depends on periodic information broadcasts to maintain the routing tables, therefore more energy is consumed. One dramatic example of the difference in average energy consumption between DSDV and DSR is observed in the case of 2 streams. The number of periodic information exchanges is large compared to the number of packets transmitted. In proactive routing protocols like DSDV, the routing overhead is so large especially in idle networks that it has great impact on the energy consumption.

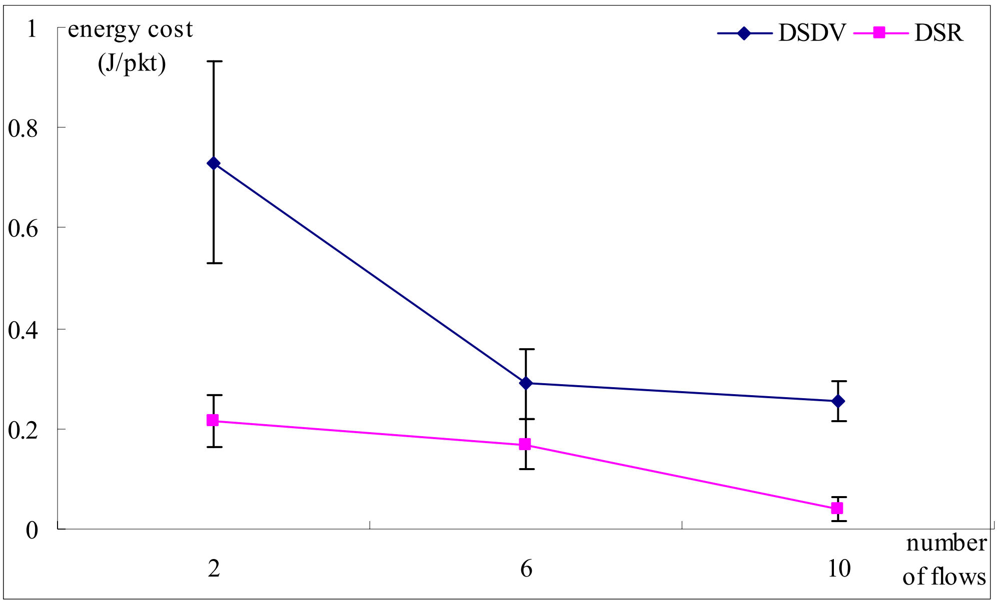


Figure 3.11 Average energy consumption

3.6 Conclusion

A number of simulations are performed in this chapter, resulting in comparison results in five different metrics. DSR has a higher packet delivery ratio than DSDV in cases of

2, 6 and 10 streams. Meanwhile, DSR outperforms DSDV in terms of energy consumption. At the other end of the spectrum, DSDV behaves better in other three metrics, delay, jitter and throughput.

For a network operator who strives to offer reliable packet delivery service, DSR is better a solution compared to DSDV. On the contrary, for a time sensitive application, DSDV is preferred. To conclude, different metrics may lead to different protocol preference. In case of a single metric, the protocol selection is easy. However, when the number of metrics increases, the protocol selection becomes much more difficult since the absence of an overall performance evaluation method which is the focus of the next two chapters.

Chapter 4 Performance evaluation with SAW-AHP, GRA and TOPSIS

Extensive simulations are performed and results are analysed in the last chapter. However, an overall function, incorporating impact of different QoS metrics is absent. In this chapter, a method which combines the simple additive weighting and analytic hierarchy process (SAW-AHP) is proposed to obtain a weighting function for protocol performance based on which protocols can be ranked. Meanwhile, GRA and TOPSIS are applied for benchmarking.

The chapter is organized as follows. Section 4.1 describes the proposed SAW-AHP based on which alternatives are ranked. For comparison, two other methods, GRA and TOPSIS, are studied in the following two sections. Section 4.4 conducts some simulations and compares the results. A new metric, synthetic improvement ratio index (SIRI), is developed in section 4.5. A comparison of the three methods concludes this chapter.

4.1 SAW-AHP

AHP has been applied successfully in a number of practical Multi-Criteria Decision Making (MCDM) problems. In spite of its popularity, the validity of AHP has been discussed ever since its introduction. The discussion has concentrated on four areas [150], rank reversal [153]-[158], inconsistent judgement [159][160], the 1-9 fundamental scale [161][162] as well as the axioms of the pair-wise comparison [163]. Most of those problems have been solved at least for three-level hierarchy structure

[150][164]-[167] and this thesis will not contribute further to this discussion. This chapter targets performance evaluation of alternative routing protocols in MANETs with SAW-AHP.

Figure 4.1 shows the computation procedure of SAW-AHP. As can be seen, the AHP method is adopted to obtain the weights for QoS metrics first. The following step is to define the attributes of these metrics, using algorithms in SAW, and thereby construct pair-wise matrices based on which weights for alternatives under different metrics can be derived via AHP.

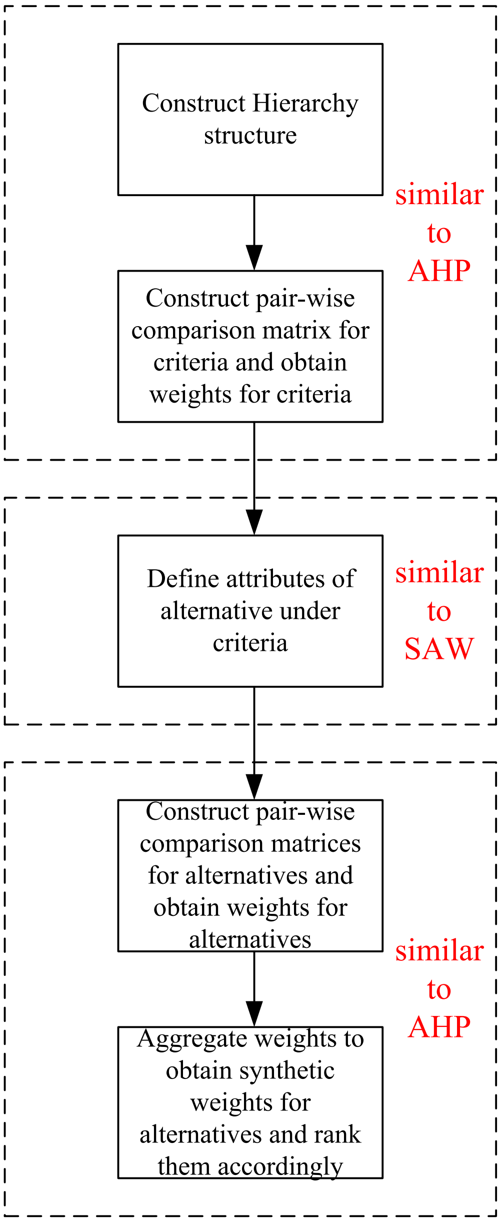


Figure 4.1 SAW-AHP

4.1.1 Hierarchy structure

The objective of the BEQoS model in this thesis is to find the best routing protocol from among several alternatives in a MANET according to the preference of a number of QoS metrics which are treated as criteria. The process of selecting the criteria is described in this section.

One main target of a MANET is to exchange information reliably. As a consequence, packet delivery ratio (PDR), which reflects the reliability of the whole network, is selected.

Delay reveals the network's efficiency and is a critical criterion especially for time-sensitive systems. Therefore, delay is accepted as a criterion. There are some factors that influence the delay. The distance from the source to the destination, together with time required by every hop largely dictate the total delay. The optimum route should have the smallest delay.

Every packet may reach the destination with different delays due to factors such as congestion and collision, and the difference is measured by jitter. Jitter is of great importance for live videos and thus it is considered as a criterion.

The throughput reflects the network resource utilization. It is a valuable metric for a network operator. An ideal routing protocol allocates traffic evenly and thus a higher throughput is achieved.

Besides QoS metrics, energy cost is considered because many mobile devices are battery-powered and lower energy consumption will prolong the lifetime of the node as well as the system.

The criteria stated above are common in most work and they reflect the network performance very well. Two alternatives that are considered in this thesis are DSDV, which is a proactive routing protocol, and DSR, which is a reactive protocol. Figure 4.2 shows the hierarchy structure with three layers, the objective layer, criteria layer and alternative layer.

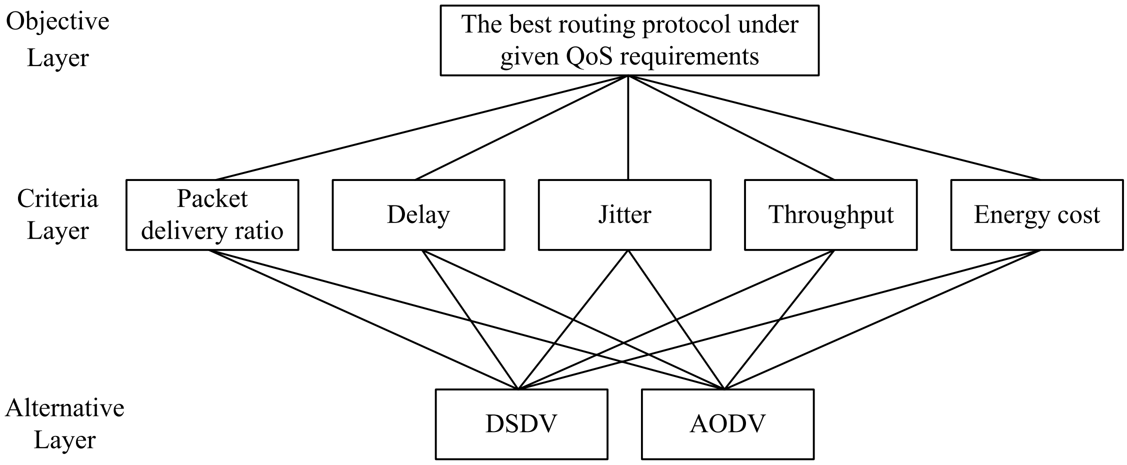


Figure 4.2 Hierarchy structure

After obtaining the hierarchy structure, the first step is to compute the weights for metrics. Besides AHP method, Genetic algorithm (GA) [168] [169], which is based on the natural genetics theory, is also a popular method to derive weight for metrics. However, selecting GA parameters like is challenging due to the possible variations and combinations in the algorithm operators and objective functions [170]. Therefore, GA is not applied in this thesis.

4.1.2 Pair-wise comparison matrix and weights for metrics

A decision maker is assumed to be able to compare any two elements, say E_i and E_j, at the same level of the hierarchy structure and provide a numerical value e_{ij} according to his/her preference as shown in (4.1)

$$E = \begin{pmatrix} 1 & e_{12} & e_{13} & \cdots & e_{1n} \\ e_{21} & 1 & e_{23} & \cdots & e_{2n} \\ e_{31} & e_{3n} & 1 & \cdots & e_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ e_{n1} & e_{n2} & e_{n3} & \cdots & 1 \end{pmatrix} \tag{4.1}$$

where n denotes the number of elements in a single layer, $e_{ij} > 0$ for any i=1,2,…,n and j=1,2,…,n. The reciprocal property

$$e_{ji} = \frac{1}{e_{ij}} \tag{4.2}$$

holds in matrix (4.1). Consequently, $n(n-1)/2$ comparisons are represented in matrix (4.1). The fundamental scales for pair-wise comparison in [171] could serve as a good basis and they are itemized in Table 4.1.

Table 4.1 The fundamental scales for pair-wise comparison

Degree of importance	Definition	Explanation
1	**Equal importance**	Two elements contribute equally to the objective
3	**Moderate importance**	Experience and judgment slightly favour one element over another
5	**Strong importance**	Experience and judgment strongly favour one element over another
7	**Very strong importance**	One element is favoured very strongly over another; its dominance is demonstrated in practice
9	**Extreme importance**	The evidence favouring one element over another is of the highest possible order of affirmation
Intensities of 2,4,6 and 8 can be used to express intermediate values.		

Prior to obtaining the pair-wise comparison matrix for criteria, several assumptions are made for the relative importance of criteria in this thesis. They are as follows:

(I) Packet delivery ratio is moderately more important than delay;

(II) Packet delivery ratio is moderately more important than jitter;

(III) Packet delivery ratio and throughput are equally important;

(IV) Packet delivery ratio is moderately more important than energy cost;

(V) Delay and jitter are equally important;

(VI) Delay and energy cost are equally important;

(VII) Jitter and energy cost are equally important;

(VIII) Throughput is moderately more important than delay;

(IX) Throughput is moderately more important than jitter;

(X) Throughput is moderately more important than energy cost.

Generally, these parameters are application dependent and the choices here are for a specific application scenario.

According to Table 4.1, the above 10 assumptions lead to the comparison matrix for criteria as follows

$$C = \begin{pmatrix} 1 & 3 & 3 & 1 & 3 \\ \frac{1}{3} & 1 & 1 & \frac{1}{3} & 1 \\ \frac{1}{3} & 1 & 1 & \frac{1}{3} & 1 \\ 1 & 3 & 3 & 1 & 3 \\ \frac{1}{3} & 1 & 1 & \frac{1}{3} & 1 \end{pmatrix} \tag{4.3}$$

Matrix (4.3) is composed based on the above 10 assumptions in this thesis. However, the pair-wise comparison method is generic to other cases with different QoS requirements.

There are several methods to derive weights from a comparison matrix of which geometric mean method is a straight forward and reliable alternative [172]. The first step of the geometric mean method is to compute the root of multiplicative results of elements in the same row via

$$r_i = \prod_{j=1}^{n} (a_{ij})^{\frac{1}{n}} \tag{4.4}$$

where a_{ij} (i,j=1,2,…,n) denotes the value of ij'th elements in comparison matrix (4.3) and n is number of elements in the row. The results in (4.4) are normalized by

$$\omega_i = \frac{r_i}{\sum_{j=1}^{n} r_j} \tag{4.5}$$

Applying formula (4.4) and (4.5) to matrix (4.3), the normalized weights for criteria are obtained in Table 4.2. As observed, the weights for packet delivery ratio and throughput are equal, indicating the same importance of those two metrics. Delay, jitter and energy cost have the same weight which accounts for one third of that for packet delivery ratio, revealing that they are less important compared to packet delivery ratio. Qualitatively, a protocol that has a better performance in terms of packet delivery ratio and throughput is more likely to be selected based on results in Table 4.2.

Table 4.2 Weights for criteria

Criterion	**Weight**
Packet delivery ratio	0.333
Delay	0.111
Delay jitter	0.111
Throughput	0.333
Energy cost	0.111

One of the most favourite properties of AHP is its capability of measuring the consistency of the decision maker based on the idea of cardinal transitivity. In AHP, a matrix M is consistent if and only if $a_{ik} \times a_{kj} = a_{ij}$, where a_{ij} is the ij'th element of the matrix [172]. However, this condition can rarely be satisfied in practice, especially in scenarios with a large number of criteria or alternatives. The violation level of consistency changes with person or context. Satty [171] developed a metric, Consistency Ratio (C.R.), to indicate the extent to which the consistency is violated with two steps. Firstly, the maximum eigenvalue for the pair-wise comparison matrix is calculated by

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(C\omega)_i}{\omega_i} \tag{4.6}$$

where C and ω_i denote the pair-wise comparison matrix and weight for the i'th element respectively, n represents the number of elements. The consistency ratio, C.R., is calculated using

$$C.R. = \begin{cases} \dfrac{\left(\dfrac{\lambda_{\max} - n}{n-1} \right)}{R.I.} & n > 2 \\ 0 & n = 1, 2 \end{cases} \tag{4.7}$$

where $R.I.$ is the random index of a pair-wise comparison matrix that depends on the number of elements in the matrix as itemized in Table 4.3.

Table 4.3 Random inconsistency index (R.I.) ([171])

Number of elements	3	4	5	6	7
Random Index (R.I.)	0.58	0.90	1.12	1.24	1.32

The maximum eigenvalue for criteria, is computed by applying (4.6) to matrix (4.3), resulting in $\lambda_{max} = 5$. Consequently, the consistency ratio of matrix (4.3) equals 0 which is below the pre-defined threshold of 0.1 in [171]. It is thereby concluded that the comparison matrix (4.3) is consistent.

4.1.3 Defining attribute for QoS metrics

Instead of using scales in Table 4.1, simulation results obtained in the last chapter, listed in full in Appendix C, are employed to construct the pair-wise comparison matrices for alternatives for the sake of accuracy. However, the attributes of metrics is different; some metrics like packet delivery ratio are "the larger the better" whereas others like delay are "the smaller the better". AHP is not capable of solving such problems and thus SAW is used to define attributes of metrics and construct pair-wise comparison matrices for alternatives accordingly.

Table 4.4 summarizes the attributes of metrics in this thesis. As seen, two metrics, packet delivery ratio and throughput, are grouped into the "the larger the better" category while the other three metrics, delay, jitter and energy cost, are allocated to the "the smaller the better" category.

Table 4.4 Criteria and attribute

Criterion	Description
Packet delivery ratio	**the larger the better**
Delay	**the smaller the better**
Delay jitter	**the smaller the better**
Throughput	**the lager the better**
Energy cost	**the smaller the better**

In SAW, simulation results have to be normalized before performing pair-wise comparisons. For metrics that are the larger the better, the normalized value d_i^{norm} is

$$d_i^{norm} = \frac{d_i}{\max\{d_i\}} \tag{4.8}$$

where d_i denotes empirical data from simulations whereas for the parameters that are the smaller the better, the normalized value d_i^{norm} is

$$d_i^{norm} = \frac{\min\{d_i\}}{d_i} \tag{4.9}$$

4.1.4 Construction of pair-wise comparison matrices for alternatives

After empirical data from simulations are normalized, pair-wise comparisons are performed. For simplicity, but without loss of generality, the detailed procedure of computing weights for alternatives in the case of 2 traffic streams is provided. The value of the corresponding element in the pair-wise comparison matrix for alternatives equals

$$a_{ij} = \frac{d_i^{norm}}{d_j^{norm}} \tag{4.10}$$

where d_i^{norm} and d_j^{norm} denote normalized simulation results obtained via formula (4.8) or (4.9). The reciprocal relation in formula (4.2) still holds. Therefore, the comparison matrix, under the criteria of packet delivery ratio which is "the larger the better", is

$$A_1 = \begin{pmatrix} 1 & \frac{94.7}{99.1} \\ \frac{99.1}{94.7} & 1 \end{pmatrix} \tag{4.11}$$

On the contrary to packet delivery ratio, delay is classified as a "the smaller the better" metric and thereby the comparison matrix for alternatives under delay, using normalization method in formula (4.9) becomes

$$A_2 = \begin{pmatrix} 1 & \dfrac{2.68}{1.98} \\ \dfrac{1.98}{2.68} & 1 \end{pmatrix} \tag{4.12}$$

Similar to delay, the metric jitter is also categorized as “the smaller the better”, thereby the comparison matrix, under the metric jitter, is

$$A_3 = \begin{pmatrix} 1 & \dfrac{2.91}{2.41} \\ \dfrac{2.41}{2.91} & 1 \end{pmatrix} \tag{4.13}$$

Throughput is different from delay and jitter in the way that it belongs to “the larger the better” class, the normalization method in formula (4.8) is used to reach the compassion matrix for DSDV and DSR under throughput

$$A_4 = \begin{pmatrix} 1 & \dfrac{3.68}{3.38} \\ \dfrac{3.38}{3.68} & 1 \end{pmatrix} \tag{4.14}$$

For the metric energy cost, a smaller value is favoured which is similar to that of delay and jitter. Hence for the scenario of 2 traffic flows, under the criterion of energy cost, the comparison matrix becomes

$$A_5 = \begin{pmatrix} 1 & \dfrac{0.214}{0.730} \\ \dfrac{0.730}{0.214} & 1 \end{pmatrix} \tag{4.15}$$

Applying the geometric mean method in formula (4.4) and (4.5), the normalized weights for DSDV and DSR under five metrics, packet delivery ratio, delay, jitter, throughput and energy cost can be obtained as shown in Table 4.5.

As seen, DSR has larger weights in terms of packet delivery ratio and energy cost, indicating its better performance over DSDV. On the contrary, the weights for DSDV exceed those for DSR in three other metrics, revealing DSDV's better performance in delay, jitter and throughput. These two conclusions are that the same as those from the simulations in the previous chapter.

Table 4.5 Weights for alternatives (2 streams)

Criterion	Weights	
	DSDV	DSR
packet delivery ratio	0.489	0.511
Delay	0.575	0.425
Jitter	0.547	0.453
Throughput	0.521	0.479
energy cost	0.227	0.773

The weights for DSDV and DSR with 6 and 10 traffic streams can be obtained with similar method described above. The results are itemized in Appendix D. Since there are only two elements in the comparison matrices for alternatives, those matrices are consistent [172].

4.1.5 Synthetic weights

The final step of the proposed SAW-AHP method is to compute the synthetic weights' aggregation via

$$s\omega_j = \sum_{i=1}^{n} c_i \omega_{ij} (i, j = 1, ..., n) \qquad \textbf{(4.16)}$$

where $s\omega_j$ denotes the synthetic weights for the $j^{'th}$ alternative, c_i symbolize weights for the $i^{'th}$ metric and ω_{ij} represents the weight for the $j^{'th}$ alternative under the $i^{'th}$ metric. The alternative with the largest synthetic weight is considered to the optimal one. Actually, the aggregating algorithm in (4.16) is a kind of utility function.

Combining formula (4.16) with results in Table 4.5, the synthetic weights for DSDV and DSR are computed for the case of 2 traffic flows. In the same manner, the synthetic weights for alternatives DSDV and DSR for 6 and 10 traffic streams can be obtained and these results are shown in Figure 4.3. It is observed that DSR outperforms DSDV in the 2 traffic streams case. However, DSDV behaves better as the number of traffic streams increases to 6. For the scenarios where the number of flows is 10, DSDV is better than DSR. To conclude, DSR is preferred when traffic volume is small while DSDV is favoured when the network traffic increases. Based on Figure 4.3, the ranking order can be obtained as shown in Table 4.6.

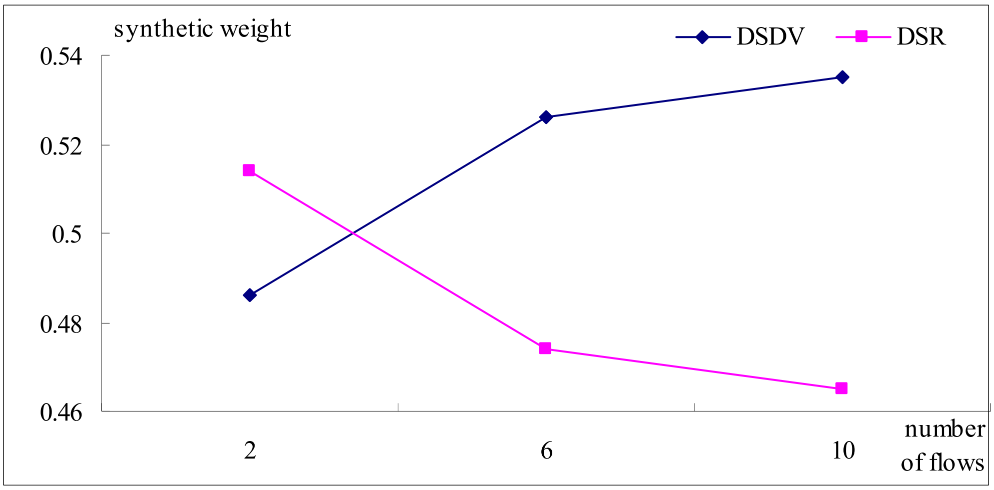


Figure 4.3 Synthetic weight

Table 4.6 Ranking order for DSDV and DSR (SAW-AHP)

Number of flows	**Ranking order**
2	DSDV<DSR
6	DSDV>DSR
10	DSDV>DSR

4.2 Grey relational analysis (GRA)

In addition to the proposed SAW-AHP method, the grey relational analysis is another method to rank alternatives in multi-criteria decision problems. In this thesis, GRA is adopted for benchmarking. For simplicity but without loss of generality, the case of 2 traffic streams is studied. However, this method is generic to other scenarios. As stated in section 2.5.2.5, GRA involves fives steps as follows.

4.2.1 Defining attributes of metrics

Metrics are classified into one of two categories, the lager the better and the smaller the better. This step is quite similar to that in section 4.1.3 and the results are identical with those in Table 4.4.

4.2.2 Determining low bound or high bound values

Table 4.7 Low bound and high bound (2 traffic streams)

	metrics				
	packet deliver ratio	**delay**	**jitter**	**throughput**	**energy cost**
DSDV	0.947	1.98 ms	2.41 ms	3.68 Mbps	0.730 J/pkt
DSR	0.991	2.76 ms	2.84 ms	3.38 Mbps	0.214 J/pkt
attributes	the larger the better	the smaller the better	the smaller the better	the larger the better	the smaller the better
low/high bound	low bound 0.947	high bound 2.76 ms	high bound 3.87 ms	low bound 3.38 Mbps	high bound 0.730 J/pkt

Table 4.7 itemizes the low or high bound for five metrics. In GRA, the high bound is used in the normalization process when the metric is “the larger the better”. On the contrary, the low bound is used when the metric is classified as “the smaller the

better".

4.2.3 Normalization

To eliminate the units in different metrics, normalization is performed in GRA. For a metric whose attribute is "the larger the better", the normalized value of the $i^{'th}$ alternative under the $j^{'th}$ metric (criteria) is

$$s_{ij} = \frac{d_{ij} - l_j}{u_j - l_j} \tag{4.17}$$

where d_{ij} denotes performance of the $i^{'th}$ alternatives under the $j^{'th}$ metric, $u_j = max\{d_{ij}\}$ and $l_j = min\{d_{ij}\}$. The normalized value of a "the smaller the better" metric is

$$s_{ij} = \frac{u_{ij} - d_j}{u_j - l_j} \tag{4.18}$$

The normalized values for DSDV and DSR can be obtained via applying (4.17) and (4.18) and they are presented in Table 4.8.

Table 4.8 Normalized value for alternatives (2 traffic streams)

alternatives	**metric**				
	packet delivery ratio	**delay**	**jitter**	**throughput**	**energy cost**
DSDV	0	1	1	1	0
DSR	1	0	0	0	1

4.2.4 Computing Grey relational coefficient (GRC)

The key step of GRA is to calculate the GRC based on which the alternatives are ranked. The grey relational coefficient for the $i^{'th}$ alternative is

$$GRC_i = \frac{1}{\sum_{j=1}^{k} \omega_j \left| s_{ij} - s_j \right| + 1} \tag{4.19}$$

where ω_j denotes the weights for the j'th metric, s_j symbolizes the ideal solution and $s_j = max\{s_{ij}\}$. However, GRA is not able to derive weights for metrics. For simplicity but without loss of generality, the weights from the SAW-AHP method, as shown in Table 4.2, are used.

Figure 4.4 itemizes the GRC values for both DSDV and DSR. As seen, the GRC values for DSDV and DSR are constant at 0.693 and 0.643 respectively. According to the ranking rules in GRA, the alternative with a larger GRC is the desired one and thereby the ranking order is achieved and shown in Table 4.9. As seen, the GRC of DSDV exceeds that of DSR in all three cases.

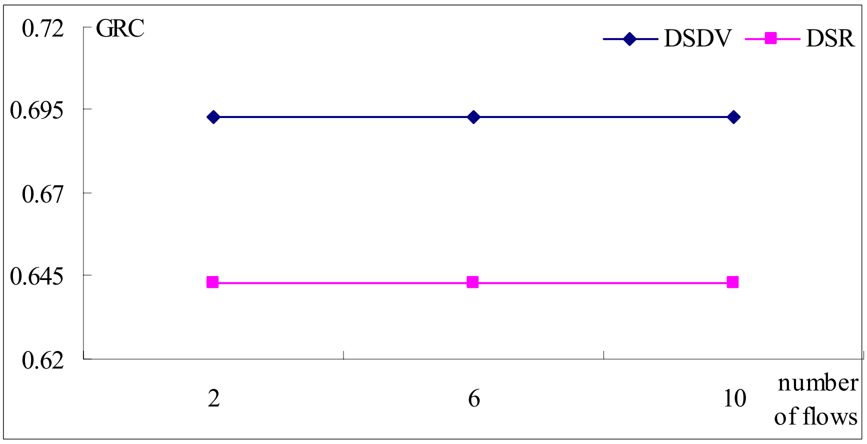


Figure 4.4 GRC for DSDV and DSR

Table 4.9 Ranking order for DSDV and DSR (GRA)

Number of flows	Ranking order
2	DSDV>DSR
6	DSDV>DSR
10	DSDV>DSR

4.3 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

In addition to the two methods above, TOPSIS is also a widely adopted method in MCDM problems. In this thesis, GRA is adopted for benchmarking. Again, the performance of DSDV and DSR in the 2 traffic streams network is studied. To begin with, a decision matrix composed of performance of alternatives is constructed as follows

$$D = \begin{bmatrix} 0.947 & 1.98 & 2.41 & 3.68 & 0.730 \\ 0.991 & 2.68 & 2.91 & 3.38 & 0.214 \end{bmatrix} \tag{4.20}$$

where the first row contains performance of DSDV in terms of packet delivery ratio, delay, jitter, throughput and energy cost whereas the second row contains results of DSR. The elements in the decision matrix are normalized as

$$s_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^{k} d_{ij}^{2}}} \tag{4.21}$$

where d_{ij} denotes elements in matrix (4.20). With formula (4.21), the normalized decision matrix becomes

$$D_{norm} = \begin{bmatrix} 0.691 & 0.594 & 0.638 & 0.736 & 0.960 \\ 0.723 & 0.804 & 0.770 & 0.676 & 0.281 \end{bmatrix} \tag{4.22}$$

The weighted decision matrix V can be obtained by

$$V = D_{norm}\omega^{T} \tag{4.23}$$

where ω denotes the weights matrix for metrics. Similar to GRA, TOPSIS is also not capable of deriving weights for metrics. Without loss of generality, the weights from the SAW-AHP method as shown in Table 4.2 are assumed. Therefore the weighted normalized matrix becomes

$$V = \begin{bmatrix} 0.230 & 0.0660 & 0.0708 & 0.245 & 0.107 \\ 0.241 & 0.0893 & 0.0855 & 0.225 & 0.0312 \end{bmatrix} \tag{4.24}$$

The fourth step is to determine the ideal solution A^{+} and negative-ideal A^{-} solution. For metrics that are "the larger the better", the maximum value is preferred while for a "the smaller the better" metrics, the minimum value is selected. The ideal solution and negative-ideal solution in matrix (4.24) are

$$A^{+} = \begin{bmatrix} 0.241 & 0.0660 & 0.0708 & 0.245 & 0.0312 \end{bmatrix} \tag{4.25}$$

$$A^{-} = \begin{bmatrix} 0.230 & 0.0893 & 0.0855 & 0.225 & 0.107 \end{bmatrix} \tag{4.26}$$

The following step computes the distance of each alternative from the ideal solution using the formula

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} (v_{ij} - a_{ij}^{+})^2} \tag{4.27}$$

where v_{ij} and a_{ij} denote elements in the weighted normalized matrix (4.24) and the ideal solution matrix, (4.25) respectively, and the distance from the negative-ideal solution S_i^{-} equals

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - a_{ij}^{-})^2} \tag{4.28}$$

where a_{ij}- is element in the negative-ideal matrix (4.26). The distance from both the ideal and negative-ideal solutions of DSDV and DSR, using formula (4.27) and (4.28), are summarized in Table 4.10.

Table 4.10 Distance from ideal and negative-ideal solutions

S_1^+ (DSDV)	S_1^- (DSDV)	S_2^+ (DSR)	S_2^- (DSR)
0.0760	0.0340	0.0340	0.0760

The final step is to calculate the relative closeness to the ideal solution via

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-} \tag{4.29}$$

Applying formula (4.29) to Table 4.10, the closeness of alternatives to ideal solution can be obtained and are shown in Figure 4.5. As shown, DSR has a larger value of closeness, indicating that DSR is preferred by TOPSIS when there are 2 traffic streams in the network. However, the value of closeness for DSR decreases with the increase of traffic streams. In case of 6 and 10 streams, the values of closeness for DSDV exceed that for DSR and thereby DSDV is considered better than DSR. The ranking orders for three cases are summarized in Table 4.11.

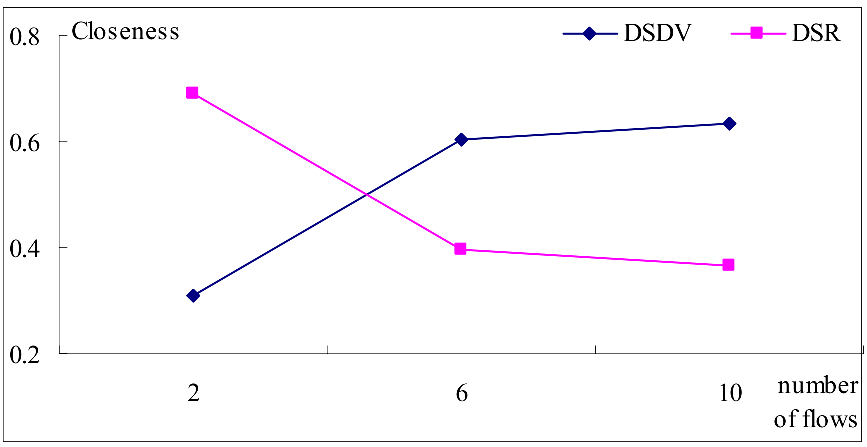


Figure 4.5 Closeness of DSDV and DSR

Table 4.11 Ranking order for DSDV and DSR (TOPSIS)

Number of flows	Ranking order
2	DSDV<DSR
6	DSDV>DSR
10	DSDV>DSR

4.4 Comparison of evaluation results

Table 4.12 summarizes the ranking orders for DSDV and DSR in three scenarios. As seen, DSDV is preferred by all three evaluation methods, SAW-AHP, GRA and TOPSIS for cases of 6 and 10 traffic streams. However, both SAW-AHP and TOPSIS favour the DSR protocol for network with 2 traffic streams while GRA prefers the DSDV. This is an example of the rank reversal problem. To solve this problem and validate the reliability of the three evaluation methods, extensive simulations are performed and a new metric, synthetic improvement ratio index (*SIRI*), is developed in the following sections.

Table 4.12 Comparison of preferred protocol

number of flows	protocol preferred		
	SAW-AHP	**GRA**	**TOPSIS**
2	DSR	DSDV	DSR
6	DSDV	DSDV	DSDV
10	DSDV	DSDV	DSDV

4.5 Performance improvement ratio

Prior to defining the synthetic improvement ratio index, a metric, the performance improvement ratio denoted by PIR, is developed to specify the level of difference between two alternatives under certain metrics.

PIR is defined as the quotient of the difference between the reference and target protocols for a value of the reference protocol. For metrics that are “the larger the better”, $PIR_{ref\text{-}tar}$ is computed via

$$PIR_{ref-tar} = \frac{P_{\mathrm{target}} - P_{\mathrm{reference}}}{P_{\mathrm{reference}}} = \frac{P_{\mathrm{target}}}{P_{\mathrm{reference}}} - 1 \tag{4.30}$$

where P_{target} and $P_{\mathrm{reference}}$ denote the performance of the target and reference protocols respectively. For “the smaller the better” metrics, $PIR_{ref\text{-}tar}$ is

$$PIR_{ref-tar} = \frac{\frac{1}{P_{\mathrm{target}}} - \frac{1}{P_{\mathrm{reference}}}}{\frac{1}{P_{\mathrm{reference}}}} = \frac{P_{\mathrm{reference}}}{P_{\mathrm{target}}} - 1 \tag{4.31}$$

A positive PIR suggests the performance improvement while a negative one reveals the deterioration.

PIRs may be aggregated by considering the weights for metrics in an application via

$$AIR_i = c_i \times PIR_i \tag{4.32}$$

where AIR_i denotes the aggregated improvement ratio for the $i^{'th}$ metric and c_i denotes the weight for $i^{'th}$ metric. AIR reflects the impact of performance improvement/deterioration of a metric on the overall QoS satisfaction. AIRs are synthesized to obtain the synthetic improvement ratio index (SIRI)

$$SIRI = \sum_{i=1}^{n} AIR_i \tag{4.33}$$

A positive SIRI is desired because it indicates system improvement when a target protocol is selected. On the contrary, a negative SIRI reveals performance deterioration if the target protocol is selected.

4.6 Simulations

Three groups of simulations corresponding to 2, 6, 10 traffic streams are performed for comparison and each group has 4 sets of simulations as shown in Figure 4.6. As shown, both simulation #1 and simulation #3 continue to employ the same protocol whereas the other two switch to a different protocol. Simulation #1 and simulation #2 are combined to determine the effect of switch from DSDV to DSR whereas simulation #3 and simulation #4 are combined to reveal the effectiveness of the switch to DSDV.

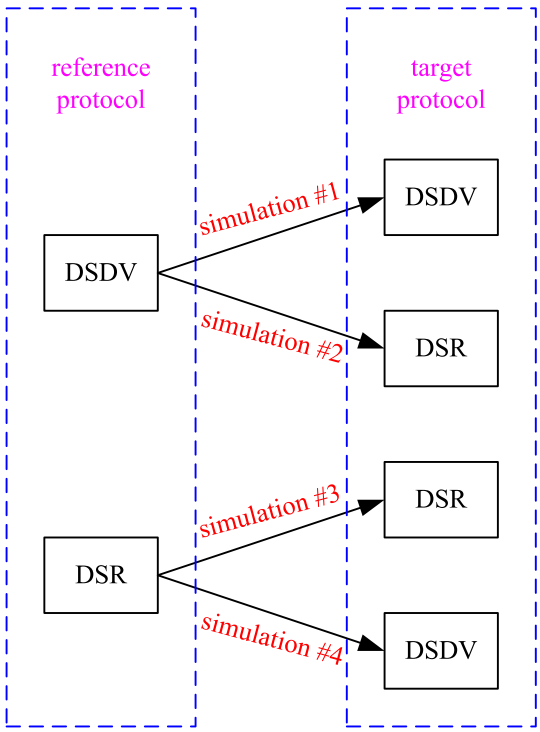


Figure 4.6 Simulations for comparison

4.6.1 2 traffic streams

Table 4.13 shows the simulation results for the case of 2 traffic streams based on which the SIRI is computed.

Table 4.13 Performance results (2 flows)

metric	simulation #1		simulation #2		simulation #3		simulation #4	
	avg	**std**	**avg**	**std**	**avg**	**std**	**avg**	**std**
PDR (%)	94.7	2.58	99.1	1.5	99.1	1.40	94.8	2.50
delay (ms)	1.98	0.235	2.68	0.445	2.68	0.45	1.99	0.238
jitter (ms)	2.41	0.155	2.91	0.233	2.91	0.234	2.41	0.159
throughput (Mb/s)	3.68	0.115	3.38	0.175	3.38	0.178	3.68	0.117
energy cost (J/pkt)	0.73	0.201	0.214	0.056	0.214	0.051	0.72	0.199
*ave: average value; std: standard deviation; PDR: packet delivery ratio								

Packet delivery ratio is classified in the "the larger the better" class, therefore, formula (4.30) is applied to calculate the PIR

$$PIR_{DSDV-DSR} = \frac{99.1\%}{94.7\%} - 1 = 4.65\% \tag{4.34}$$

$$PIR_{DSR-DSDV} = \frac{94.8\%}{99.1\%} - 1 = -4.34\% \tag{4.35}$$

It is observed in (4.34) that when the DSDV is switched to DSR, a positive PIR is obtained, indicating performance improvement in terms of packet delivery ratio. On the contrary, when DSR is switched to DSDV, performance deterioration is experienced. Consequently, DSR is preferred when the metric packet delivery ratio is concerned.

Unlike packet delivery ratio, the metric delay is a "the smaller the better" parameter thereby formula (4.31) is adopted for PIR calculation as follows

$$PIR_{DSDV-DSR} = \frac{1.98}{2.68} - 1 = -26.12\% \tag{4.36}$$

$$PIR_{DSR-DSDV} = \frac{2.68}{1.99} - 1 = 34.67\% \tag{4.37}$$

As seen in (4.36), a negative *PIR* is obtained after switching, revealing a better performance of DSDV in terms of delay. This conclusion is further validated via (4.37) which shows the performance improvement if DSDV is adopted.

Similar to delay, jitter is also divided into the "the smaller the better" category and formula (4.31) is applied to compute PIR for jitter.

$$PIR_{DSDV-DSR} = \frac{2.41}{2.91} - 1 = -17.18\% \tag{4.38}$$

$$PIR_{DSR-DSDV} = \frac{2.91}{2.41} - 1 = 20.75\% \tag{4.39}$$

The result in (4.38) demonstrates a performance deterioration when DSDV is switched to DSR. On the contrary, when DSDV replaces the previous DSR protocol, a gain is achieved. To conclude, DSDV outperforms DSR in terms of jitter.

Different to delay and jitter, the metric throughput is a "the larger the better" parameter and hence formula (4.30) is utilized to compute PIR.

$$PIR_{DSDV-DSR} = \frac{3.38}{3.68} - 1 = -8.15\% \tag{4.40}$$

$$PIR_{DSR-DSDV} = \frac{3.68}{3.38} - 1 = 8.88\% \tag{4.41}$$

A negative PIR in (4.40), together with a positive value PIR (4.41), leads to the conclusion that DSDV outperforms DSR in terms of throughput.

Unlike the parameter throughput, less energy consumption is desired, thus formula (4.31) is applied, leading to

$$PIR_{DSDV-DSR} = \frac{0.73}{0.214} - 1 = 241.12\% \tag{4.42}$$

$$PIR_{DSR-DSDV} = \frac{0.214}{0.72} - 1 = -70.28\% \tag{4.43}$$

A large amount of energy is reduced via switching DSDV to DSR. This is attributed to the reactive nature of DSR which initiates route requests on demand. Much energy is spent on periodic information broadcast in DSDV and hence its energy cost is really large.

The final step is to integrate those PIRs together to achieve the final SIRI which indicates the best protocol for the case of 2 traffic streams with (4.32) and (4.33).

$$\begin{aligned} SIRI_{DSDV-DSR} &= 4.65\% \times 0.333 + (-21.12\%) \times 0.111 + (-17.18) \times 0.111 \\ &\quad + (-8.15) \times 0.333 + 241.12 \times 0.111 \\ &= 20.79 \end{aligned} \tag{4.44}$$

$$\begin{aligned} SIRI_{DSR-DSDV} &= (-4.34\%) \times 0.333 + 34.67\% \times 0.111 + 20.75\% \times 0.111 \\ &\quad + 8.88 \times 0.333 + (-70.28\%) \times 0.111 \\ &= -0.14\% \end{aligned} \tag{4.45}$$

As seen in (4.44), a positive SIRI is achieved which demonstrates the effectiveness of the protocol switch from DSDV to DSR. On the contrary, when DSDV replaces the original DSR protocol, the overall performance deteriorates as shown in (4.45). Therefore, it is concluded that DSR is more suitable for the case of 2 traffic streams.

4.6.2 6 and 10 traffic streams

Table 4.14 and Table 4.15 itemizes simulation results for 6 and 10 traffic streams based on which $SIRI_{DSDV\text{-}DSR}$ and $SIRI_{DSR\text{-}DSDV}$ are obtained, using similar procedures to that of 2 traffic flows. The results are shown in Table 4.16. As seen, DSDV should be adopted as the number of traffic streams increases from 2 to 6. When number the traffic streams increases further to 10, DSDV should still be used to avoid network performance deterioration.

Table 4.14 Performance results (6 flows)

Metric	simulation #1		simulation #2		simulation #3		simulation #4	
	Avg	**Std**	**avg**	**std**	**avg**	**std**	**avg**	**std**
PDR (%)	69.1	8.00	84.9	7.80	85.0	7.60	69.3	7.97
delay (ms)	3.63	1.01	7.87	2.13	7.88	2.15	3.66	1.03
jitter (ms)	4.01	1.67	13.9	3.42	13.9	3.44	4.02	1.69
throughput (Mb/s)	3.57	0.097	3.29	0.172	3.29	0.172	3.56	0.097
energy cost (J/pkt)	0.290	0.070	0.169	0.049	0.169	0.049	0.290	0.068
*ave: average value; std: standard deviation; PDR: packet delivery ratio								

Table 4.15 Performance results (10 flows)

Metric	simulation #1		simulation #2		simulation #3		simulation #4	
	Avg	**Std**	**avg**	**std**	**avg**	**std**	**avg**	**std**
PDR (%)	65.7	7.23	82.3	6.35	82.4	6.33	65.8	7.21
delay (ms)	3.58	0.745	9.81	2.74	9.85	2.80	3.61	0.752
jitter (ms)	4.37	1.18	14.3	4.15	14.4	4.23	4.45	1.26
throughput (Mb/s)	3.55	0.091	3.25	0.150	3.25	0.153	3.54	0.093
energy cost (J/pkt)	0.256	0.040	0.185	0.026	0.185	0.025	0.255	0.038
*ave: average value; std: standard deviation; PDR: packet delivery ratio								

Table 4.17 compares the simulation results with three performance evaluation methods, SAW-AHP, GRA and TOPSIS. As seen, the results achieved via SAW-AHP and TOPSIS are identical to the simulation results whereas GRA, in spite of successful applications in other areas, suffers from the rank reversal problem which, by definition,

refers to inappropriate ordering of alternatives in this thesis. The ranking reversal problem is also observed in by A. Husazk *et al.* [173] who attributes this rank reversal problem to inappropriate normalization methods.

Table 4.16 Synthetic improvement ratio index (6 and 10 traffic flows)

	metric	**6 traffic streams**		**10 traffic streams**	
		DSDV-DSR	**DSR-DSDV**	**DSDV-DSR**	**DSR-DSDV**
PIR	**packet deliver ratio**	22.87%	-18.47%	25.27%	-20.15%
	delay	-53.88%	115.30%	-63.51%	172.85%
	jitter	-71.15%	245.78%	-69.44	223.60%
	throughput	-7.84%	8.21%	-8.45%	8.92%
	energy cost	71.60%	-41.72%	38.38%	-27.45%
SIRI		-0.93%	32.03%	-4.90%	37.22%

Table 4.17 Reliability comparison of three evaluation methods

number of flow	**routing protocol preferred**			
	SAW-AHP	**GRA**	**TOPSIS**	**simulation**
2	DSR	DSDV	DSR	DSR
6	DSDV	DSDV	DSDV	DSDV
10	DSDV	DSDV	DSDV	DSDV

4.7 An application of SAW-AHP in adaptive protocol selection in MANETs

In current cellular networks, each mobile user is attached to a single network in which services such as voice, SMS and Internet access are provided. In such networks, network selection (cellular handover) is almost solely controlled by the network operator, targeting at maintaining connectivity, improving communication quality and balancing traffic. QoS satisfaction is not always considered in cellular networks.

However, with the increase of time sensitive applications, QoS provision is desired in wireless communications. As a result, the network operator is expected to upgrade the current system so that QoS requirements of different users can be satisfied at some extent. Nevertheless, due to the dynamic link quality and user mobility, QoS provision is highly time and location dependent. Consequently, an efficient and reliable protocol selection process is desired to initialize and maintain the session connectivity whilst also satisfying the users' requirements. This section focuses on proposing an adaptive protocol selection framework that considers the all users' QoS preference with SAW-AHP.

4.7.1 Framework of the adaptive system

The existed adaptive algorithms in MANETs do not address clearly the roles of terminals and network operators, leading to unrealistic architecture design. In [170], M. M. ALkhawlani proposes an integrated user-centric and operator centric model. In this model, the user sends his/her viewpoint of the selection decision which is mainly based on the preference and experience of operators to the network operator. On receiving the decision from the user, the operator also evaluates alternatives according to network conditions.

In this thesis, the selection decision is made at the network operator (access point). Arguments in favour of this include the two facts. To begin with, the users are always battery powered and therefore complex decision making should be avoided. Secondly, the access point is well informed about the network conditions and it is much more powerful than the terminal it terms of computation ability and energy supply. The adaptive model include three components, protocol selection trigger which activates the protocol selection process, protocol selection decision which aggregates all user's QoS preference and determines the optimal protocol as well as protocol selection execution.

4.7.1.1 Protocol selection trigger

The protocol selection is invoked either at the beginning of a session or when the current connectivity breaks down unexpectedly.

As shown in Figure 4.7, when one session starts, the source firstly generates a dedicated packet, describing the user's QoS preference, for the access point if the route to the destination is available. As long as the path to the destination is unknown, the source will initialize the route discovery process until a route is found after which the QoS preference description packet will be sent to the access point by the source.

Besides new sessions, a route breakage may also trigger the protocol selection as shown in Figure 4.7 Protocol selection triggersFigure 4.7. In this case, a new route will be discovered before the source generates the QoS preference description packet for the access point.

4.7.1.2 Protocol selection decision

The successful reception of a QoS description packet at the access point marks the beginning of the protocol selection decision process as shown in Figure 4.8. As seen, the newly received QoS preference description packet, together with current network conditions (e.g. traffic volume, congestion) determines the selected protocol at the access point. As long as uncertainty such as standard deviation is marginal, SAW-AHP is adopted for efficiency. If uncertainty can not be neglected, FPP is employed.

Alternatives are re-evaluated for previous QoS streams. If one alternative protocol, say A, is preferred by a given stream, say, m_1, then A is assigned one ticket. Alternative with the most tickets are selected as the preferred protocol and the result is broadcasted through the network based on which new protocol is adopted.

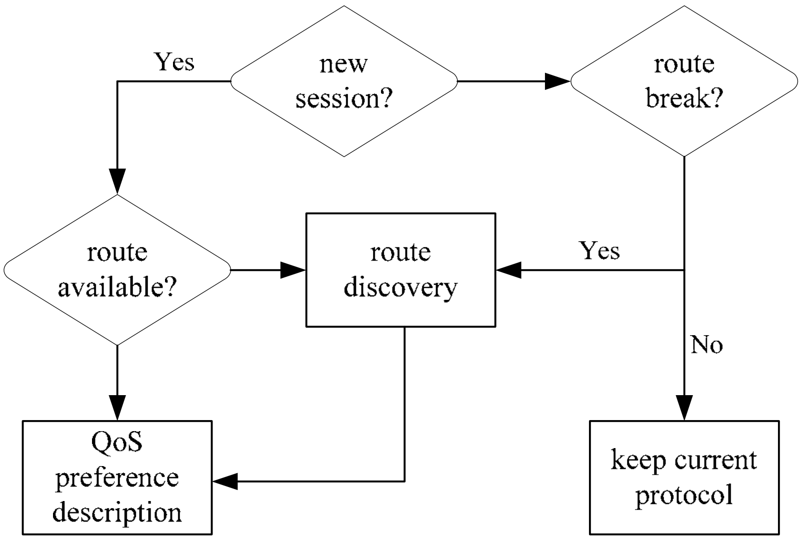


Figure 4.7 Protocol selection triggers

4.7.1.3 Protocol selection execution

As all sources receives the protocol selection decision packet from the access point, sources will record this information and attach it to every data packet so that relay nodes are able to apply the corresponding routing protocol until the packet reaches the destination. In this manner, traffic transmission continues until the connection breaks or the completion of the current session.

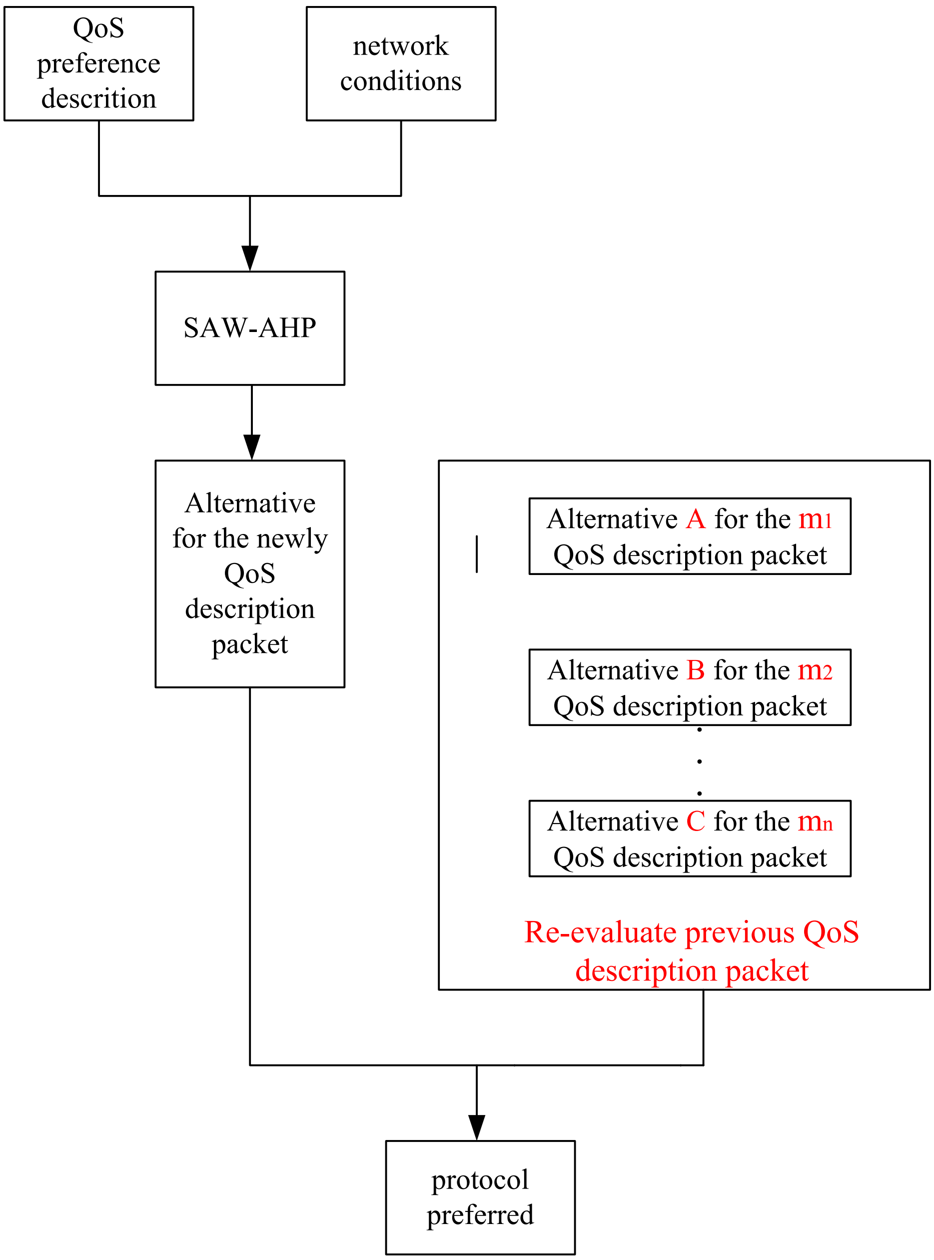


Figure 4.8 Block diagram of protocol selection decision

4.8 Costs and gains

This section focuses on discussion of additional cost of deploying such adaptive model.

4.8.1 Processor load

A separate QoS preference description packet is necessary at the beginning of a new session or after a connection breaks, incurring additional processor load at the terminal. This load is marginal if the connection is stable.

Processors in relay nodes have to de-capsulate the data packets to obtain the selected routing protocol which will introduce additional costs. However, these costs are comparatively small because only the bits of concern are analyzed.

Thirdly, it takes some time for the processor at the access point to evaluate and make a protocol selection decision. This load may be ignored because the access point is very powerful and SAW-AHP is complicated.

4.8.2 Additional network traffic

The QoS preference description process involves several relay nodes in addition to the source and access point which contributes to the increase of network traffic. This happens at the start of a session and link break. In a slowly changing network, the cost of QoS preference description process is comparatively smaller.

Moreover, protocol selection result is broadcast through the network, leading to additional cost. In a network where sessions start frequently but last shortly, this cost could be large.

Meanwhile, several bytes are added to the data packets, indicating selected protocol, will also induce traffic. However, this is minor compared to the large quantity of data traffic.

4.8.3 More energy consumption

This includes energy consumption of the QoS preference description, protocol selection decision process and relevant packets transmission and reception. The energy for the two above processes is very small compared with packet transmission and reception. Several bits describing the preferred routing protocol are encapsulated to every data packet and this consumes additional energy. However, the additional traffic volume is minor when the packet size is large (e.g., 512 bytes or 1K bytes).

4.8.4 Protocol switchover cost

Nodes in the network have to switch to corresponding protocol, resulting in packet drops. This cost is large in the network where network conditions such as number of traffic streams and node mobility changes dynamically.

4.9 Conclusions

QoS support routing protocols are compared independently in terms of packet delivery ratio, delay, jitter as well as throughput in much literature. It is not possible to simply aggregate several metrics together due to various units (e.g., b/s for throughput, s or ms for delay). A method, denoted by SAW-AHP, which is a combination of SAW and AHP is proposed in this thesis to rank the alternative protocols. SAW-AHP, together with other two methods GRA and TOPSIS, are used to evaluate the performance of two routing protocols DSDV, a typical proactive protocol and DSR, a typical reactive protocol and rank them accordingly.

A new metric synthetic improvement ratio index is developed, together with simulation results, to measure the reliability of evaluation methods and the results are summarized in Table 4.18. As seen, SAW-AHP and TOPSIS are able to rank alternative protocols

DSDV and DSR consistently while GRA suffers from ranking inconsistency. Therefore GRA method is not used any further in this thesis. In spite of ranking consistency of TOPSIS, it lacks a method to derive weights for metrics and so SAW-AHP is adopted.

Table 4.18 Comparison of three evaluation methods

algorithm	rank reversal	method to derive weights for metrics
SAW-AHP	No	Yes
GRA	Yes	No
TOPSIS	No	No

SAW-AHP is capable of evaluating alternative protocols reliably. Despite only one case being studied in this thesis using the SAW-AHP method, it is generic to other cases with different QoS requirements. SAW-AHP is appropriate for scenarios where the decision maker is certain about his/her preference on the performance metrics and only the average value is considered. The problems of uncertainty of preference on metrics and consideration of standard deviations in simulations will be addressed in next chapter.

An adaptive framework using the SAW-AHP evaluation results is proposed in this chapter. The cost of the adaptive framework is discussed finally.

Chapter 5 Extending SAW-AHP to SAW-FPP

SAW-AHP is a reliable and efficient method to solve Multi-Criteria Decision Making (MCDM) problems based on a decision maker's preference of alternatives. However, the decision maker is, sometimes, unable to give his/her preference in the form of specific numbers for reasons such as the uncertainty of human beings in the real world and the complexity and vagueness of the decision-making problems. As a consequence, the final ranking results may be imprecise, decreasing the credibility of the performance evaluation results [174]. To cope with such kinds of imprecise knowledge or poorly structured decision problems, Van Laarhoven *et al.* [175] extended AHP with fuzzy set theory [176] into Fuzzy AHP (FAHP) in which crisp figures are substituted by fuzzy numbers for pair-wise comparisons. In this chapter, standard deviations in simulation within Chapter 3 are considered and AHP is extended to fuzzy AHP (FAHP). Two methods, FGGM and FPP, are employed to solve the FAHP problems.

This chapter is organized as follows. The first section introduces some principles of fuzzy numbers. Section 5.2 surveys method to derive weights in FAHP. Section 5.3 constructs the fuzzy comparison matrices. The following two sections adopt the fuzzy geometric mean method as well as fuzzy preference programming to derive synthetic weights for DSDV and DSR. SIRI is extended to fuzzy SIRI (FSIRI) to measure the improvement ratio. The last section concludes this chapter.

5.1 Principles of fuzzy numbers

Prior to deriving synthetic weights for alternatives, some principles regarding fuzzy numbers are introduced for future usage.

5.1.1 Fuzzy triangular number

A fuzzy number M on R is defined to be a triangular fuzzy number if its membership function $\mu_M(x)$ has the following characteristics [184]:

(I) $0 \leq \mu_M(x) \leq 1$;

(II) $$\mu_M(x) = \begin{cases} \dfrac{x-l}{m-l} & x \in [l,m] \\ \dfrac{x-u}{m-u} & x \in [m,u] \\ 0 & otherwise \end{cases}$$

where l, m, and u denote the lower, middle and upper bounds of a triangular fuzzy number respectively, as shown in Figure 5.1.

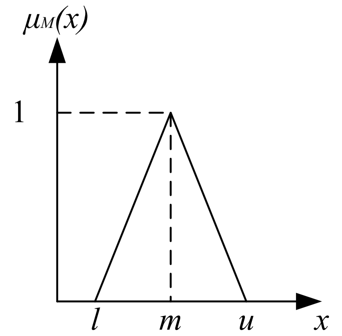


Figure 5.1 Triangular fuzzy number

The triangular fuzzy number can be expressed also by (l, m, u), and when $l = m = u$, it is a crisp number by convention. Consider two triangular fuzzy numbers M_1 and M_2 where $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the operation laws are as follows:

(I) $(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$;

(II) $(l_1, m_1, u_1) \odot (l_2, m_2, u_2) = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2)$;

(III) $(l_1, m_1, u_1)^{-1} = (\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1})$;

(IV) $\frac{(l_1, m_1, u_1)}{(l_2, m_2, u_2)} = \left(\frac{l_1}{u_2}, \frac{m_1}{m_2}, \frac{u_1}{l_2}\right)$.

5.1.2 Reciprocal relationship

Instead of using specific numbers in SAW-AHP, the elements in pair-wise comparisons matrices are represented by fuzzy triangular numbers. However, the reciprocal relationship in SAW-AHP still holds and thereby

$$\tilde{e}_{ji} = \frac{1}{\tilde{e}_{ij}} = \left(\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}\right) \tag{5.1}$$

where $\tilde{e}_{ij}=(l_{ij}, m_{ij}, u_{ij})$, representing the fuzzy comparison results of the i^{th} alternative over the j^{th} alternatives.

5.2 Methods to derive weights for fuzzy comparison matrices

To date, a number of methods have been proposed to derive weights from fuzzy comparison matrices. Van Laarhoven *et al.* [175] use a fuzzy version of Logarithmic Least Squares Method (FLLSM) to estimate weights from triangle fuzzy matrices. Buckley [172] directly fuzzifies the geometric mean method, leading to the fuzzy GMM (FGMM). Both of them begin with finding fuzzy weights for the metrics and are followed by an estimation of the fuzzy weights for alternatives. The fuzzy weights for both metrics and alternatives are synthesized to achieve the synthetic weights for alternatives in the form of fuzzy triangular numbers.

Wang *et al.* [177] revisit the fuzzy LLSM method and outline the problems in the normalization method and propose a modified LLSM method (MLLSM) [175]. The final synthetic weights for alternatives in [177] are also given in the form of fuzzy triangle numbers.

Csutora *et al.* [178] directly fuzzify the λ_{max} method (FLAMDA) to obtain the synthetic weights for alternatives in the form of fuzzy intervals to reduce fuzziness. The consistency of pair-wise comparisons is also discussed by Csutora.

Chang [179] proposes an extent analysis method (EAM) for FAHP, using triangle numbers for pair-wise comparisons. The synthetic weights for alternatives are given in the form of specific figures rather than fuzzy numbers as in [175] [177] and [178].

Mikhailov [182] decomposes fuzzy comparison results into a series of interval with different α values and this method is termed as fuzzy preference programming (FPP). The process of deriving weights is transformed into an optimisation problem which maximizes the decision-maker's satisfaction with a specific priority vector. The synthetic weights for alternatives are given in the form of crisp numbers. Mikhailov used a consistency index λ to measure the consistency of pair-wise comparisons.

The surveyed algorithms above can be classified into two main categories as shown in Figure 5.2 based on the form of the final synthetic weights. As seen, FLLSM, FGMM, MLLSM and FLAMDA result in fuzzy numbers for alternatives whereas EAM and FPP lead to crisp number results. Two methods from the two different categories will be adopted and the results are compared in this chapter. Since the geometric mean method was applied in the previous chapter, FGMM is selected. FPP is another method to derive weights for alternatives.

For simplicity but without loss of generality, the hierarchy structure for FAHP in this chapter is identical to that in Figure 4.2. The weights for metrics in Table 4.2 are assumed, the standard deviation is considered in this chapter and they are given in the form of fuzzy triangular numbers. Prior to deriving weights for alternatives and aggregating them together, the pair-wise comparison matrices for alternatives have to be constructed.

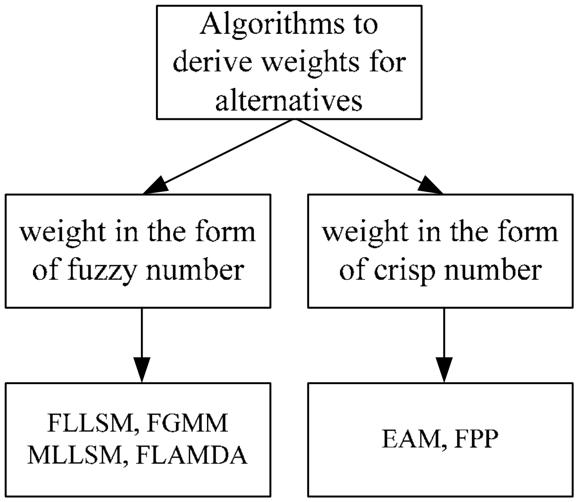


Figure 5.2 Classification of methods to derive weights

5.3 Fuzzy pair-wise comparison matrices for alternatives

The fuzzy comparison matrices are constructed based on the attributes of metrics. For "the larger the better" metrics such as packet delivery ratio and throughput, the pair-wise comparison value, $\tilde{a}_{ijk}$, for the j'th alternative over the k'th alternative under the i'th metric is given by

$$\tilde{a}_{ijk} = \frac{\left(\dfrac{(\alpha_{ij},\ \beta_{ij},\ \gamma_{ij})}{(\alpha_i(\max),\ \beta_i(\max),\ \gamma_i(\max))}\right)}{\left(\dfrac{(\alpha_{ik},\ \beta_{ik},\ \gamma_{ik})}{(\alpha_i(\max),\ \beta_i(\max),\ \gamma_i(\max))}\right)} = \frac{\left(\dfrac{\alpha_{ij}}{\gamma_i(\max)},\ \dfrac{\beta_{ij}}{\beta_i(\max)},\ \dfrac{\gamma_{ij}}{\alpha_i(\max)}\right)}{\left(\dfrac{\alpha_{ik}}{\gamma_i(\max)},\ \dfrac{\beta_{ik}}{\beta_i(\max)},\ \dfrac{\gamma_{ik}}{\alpha_i(\max)}\right)}$$

$$= \left(\frac{\alpha_{ij}}{\gamma_{ik}}\ \frac{\alpha_i(\max)}{\gamma_i(\max)},\ \frac{\beta_{ij}}{\beta_{ik}},\ \frac{\gamma_{ij}}{\alpha_{ik}}\ \frac{\gamma_i(\max)}{\alpha_i(\max)}\right) \tag{5.2}$$

where

(1) β_{ij} denotes the average performance of the j'th alternative under the i'th metric;

(2) $\alpha_{ij}=\beta_{ij}-\Delta$, Δ denotes corresponding standard deviation;

(3) $\gamma_{ij}=\beta_{ij}+\Delta$;

(4) $\alpha_i(\max)=\max\{\alpha_{i1}, \alpha_{i2},\ldots, \alpha_{im}\}$ and m denotes the number of alternatives;

(5) $\beta_i(\max)=\max\{\beta_{i1}, \beta_{i2},\ldots, \beta_{im}\}$, $\gamma_i(\max)=\max\{\gamma_{i1}, \gamma_{i2},\ldots, \gamma_{im}\}$.

For parameters that are "the smaller the better", the pair-wise comparison value $\tilde{a}_{ijk}$ becomes

$$\tilde{a}_{ijk}=\frac{\left(\dfrac{(\alpha_i(\min),\beta_i(\min),\gamma_i(\min)}{(\alpha_{ij},\beta_{ij},\gamma_{ij})}\right)}{\left(\dfrac{(\alpha_i(\min),\beta_i(\min),\gamma_i(\min)}{(\alpha_{ik},\beta_{ik},\gamma_{ik})}\right)}=\frac{\left(\dfrac{\alpha_i(\min)}{\gamma_{ij}},\dfrac{\beta_i(\min)}{\beta_{ij}},\dfrac{\gamma_i(\min)}{\alpha_{ij}}\right)}{\left(\dfrac{\alpha_i(\min)}{\gamma_{ik}},\dfrac{\beta_i(\min)}{\beta_{ik}},\dfrac{\gamma_i(\min)}{\alpha_{ik}}\right)}$$

$$=\left(\frac{\alpha_{ik}}{\gamma_{ij}}\frac{\alpha_i(\min)}{\gamma_i(\min)},\frac{\beta_{ik}}{\beta_{ij}},\frac{\gamma_{ik}}{\alpha_{ij}}\frac{\gamma_i(\min)}{\alpha_i(\min)}\right) \tag{5.3}$$

where $\alpha_i(\min)=\min\{\alpha_{i1}, \alpha_{i2},\ldots, \alpha_{im}\}$, $\beta_i(\min)=\min\{\beta_{i1}, \beta_{i2},\ldots, \beta_{im}\}$ and $\gamma_i(\min) = \min\{\gamma_{i1}, \gamma_{i2},\ldots, \gamma_{im}\}$.

For simplicity the detailed procedure of deriving weights for 2 traffic streams is presented here. As seen in Table 4.4, packet delivery ratio is classified to be a "the larger the better" metric and thereby the fuzzy comparison matrix for alternatives is given by

$$\tilde{A}_{11}=\begin{pmatrix}(1,1,1) & (\frac{92.12}{100.5}\times\frac{97.7}{100.5},\frac{94.7}{99.1},\frac{97.22}{97.7}\times\frac{100.5}{97.7}) \\ (\frac{97.7}{97.22}\times\frac{97.7}{100.5},\frac{99.1}{94.7},\frac{100.5}{97.7}\times\frac{100.5}{92.12}) & (1,1,1)\end{pmatrix} \tag{5.4}$$

Unlike packet delivery ratio, delay belongs to "the smaller the better" class and hence the fuzzy comparison matrix for DSDV and DSR, under delay, is

$$\tilde{A}_{21}=\begin{pmatrix} (1,1,1) & \left(\frac{2.23}{2.215}\times\frac{1.745}{2.215},\frac{2.68}{1.98},\frac{3.13}{1.745}\times\frac{2.215}{1.745}\right) \\ \left(\frac{1.745}{3.13}\times\frac{1.745}{2.215},\frac{1.98}{2.68},\frac{2.215}{2.23}\times\frac{2.215}{1.745}\right) & (1,1,1) \end{pmatrix} \quad (5.5)$$

Similar to delay, the formula (5.3) is used for jitter, leading to the fuzzy comparison matrix

$$\tilde{A}_{31}=\begin{pmatrix} (1,1,1) & \left(\frac{2.676}{2.565}\times\frac{2.255}{2.565},\frac{2.91}{2.41},\frac{3.244}{2.255}\times\frac{2.565}{2.255}\right) \\ \left(\frac{2.255}{3.244}\times\frac{2.255}{2.565},\frac{2.41}{2.91},\frac{2.565}{2.676}\times\frac{2.565}{2.255}\right) & (1,1,1) \end{pmatrix} \quad (5.6)$$

Unlike delay and jitter, throughput is a “the larger the better” parameter and the fuzzy comparison matrix for DSDV and DSR, under throughput, using formula (5.2) becomes

$$\tilde{A}_{41}=\begin{pmatrix} (1,1,1) & \left(\frac{3.565}{3.558}\times\frac{3.565}{3.795},\frac{3.68}{3.38},\frac{3.795}{3.202}\times\frac{3.795}{3.565}\right) \\ \left(\frac{3.202}{3.795}\times\frac{3.565}{3.795},\frac{3.38}{3.68},\frac{3.558}{3.565}\times\frac{3.795}{3.565}\right) & (1,1,1) \end{pmatrix} \quad (5.7)$$

Energy cost is a “the smaller the better” metric and hence formula (5.3) is used to obtain the fuzzy comparison matrix for alternatives.

$$\tilde{A}_{51}=\begin{pmatrix} (1,1,1) & \left(\frac{0.163}{0.931}\times\frac{0.163}{0.265},\frac{0.214}{0.730},\frac{0.265}{0.529}\times\frac{0.265}{0.163}\right) \\ \left(\frac{0.529}{0.265}\times\frac{0.163}{0.265},\frac{0.730}{0.214},\frac{0.931}{0.163}\times\frac{0.265}{0.163}\right) & (1,1,1) \end{pmatrix} \quad (5.8)$$

5.4 Fuzzy geometric mean method (FGMM)

In the geometric mean method, elements in each row are multiplied and normalized. Similarly, the normalized weights in FGMM are computed via

$$\tilde{\omega}_i = \frac{\left(\left(\prod_{j=1}^{m} \alpha_{ij}\right), \left(\prod_{j=1}^{m} \beta_{ij}\right), \left(\prod_{j=1}^{m} \gamma_{ij}\right)\right)^{\frac{1}{m}}}{\sum_{i=1}^{m}\left(\left(\prod_{j=1}^{m} \alpha_{ij}\right), \left(\prod_{j=1}^{m} \beta_{ij}\right), \left(\prod_{j=1}^{m} \gamma_{ij}\right)\right)^{\frac{1}{m}}}$$

$$= \left(\frac{\left(\prod_{j=1}^{m} \alpha_{ij}\right)^{\frac{1}{m}}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{m} \gamma_{ij}\right)^{\frac{1}{m}}}, \frac{\left(\prod_{j=1}^{m} \beta_{ij}\right)^{\frac{1}{m}}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{m} \beta_{ij}\right)^{\frac{1}{m}}}, \frac{\left(\prod_{j=1}^{m} \gamma_{ij}\right)^{\frac{1}{m}}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{m} \alpha_{ij}\right)^{\frac{1}{m}}} \right) \tag{5.9}$$

Table 5.1 itemizes fuzzy weights for packet delivery ratio, delay, jitter, throughput and energy cost, using FGMM. As seen, the values in the middle of the intervals are identical to those generated by geometric mean method in Table 4.5. However, weights for DSDV and DSR overlap with each other.

Table 5.1 Fuzzy weights for DSDV and DSR (2 streams)

Criterion	**Fuzzy weights**	
	DSDV	**DSR**
packet delivery ratio	(0.466, 0.489, 0.524)	(0.488, 0.511, 0.548)
delay	(0.295, 0.575, 0.971)	(0.220, 0.425, 0.723)
jitter	(0.380, 0.547, 0.719)	(0.315, 0.453, 0.596)
throughput	(0.432, 0.521, 0.604)	(0.396, 0.479, 0.554)
energy cost	(0.182, 0.227, 0.628)	(0.614, 0.773, 2.122)

Fuzzy weights in Table 5.1 are aggregated by

$$\tilde{s\omega}_j = \sum_{i=1}^{n} c_i \tilde{\omega}_{ij} \qquad (5.10)$$

Figure 5.3 presents synthetic weights for DSDV and DSR for cases of 2 streams. As seen, the synthetic weight for DSR overlaps with that of DSDV's. The next step is to determine which weight is larger. Optimist considers DSR to be a better solution since "DSR-2" could be larger than "DSDV-2" while pessimist regards DSR worse than DSDV due to the reason that "DSR-2" could be smaller than "DSDV-2". Similar results are also observed in [179].

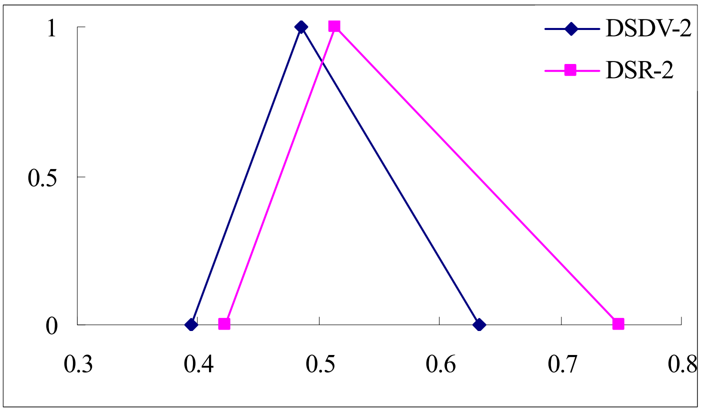


Figure 5.3 Fuzzy synthetic weight for 2 streams

Figure 5.4 and Figure 5.5 show the fuzzy synthetic weights for 6 and 10 streams respectively. Likely, those weights overlap and decision makers may achieve different conclusions.

Table 5.2 outlines ranking orders of DSR and DSDV for 2, 6 and 10 streams. As seen, optimistic and pessimistic decision makers may draw different conclusions and thus FGMM is not adopted.

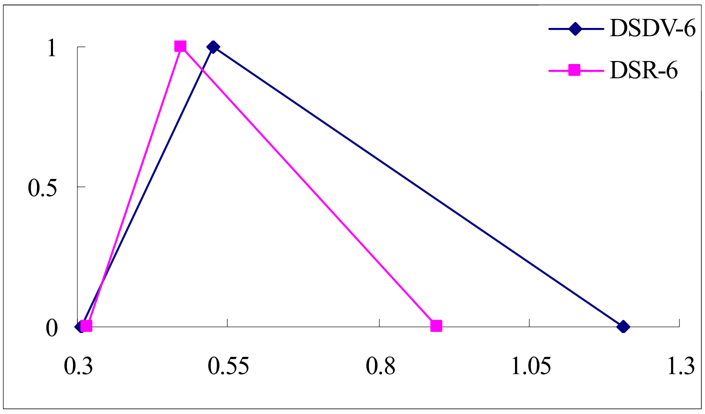


Figure 5.4 Fuzzy synthetic weight for 6 streams

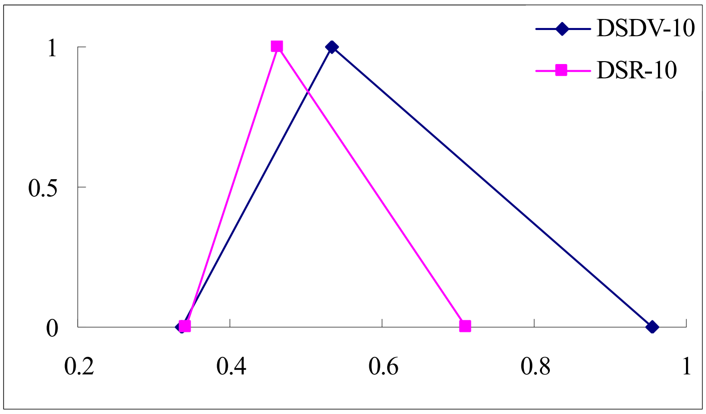


Figure 5.5 Fuzzy synthetic weight for 10 streams

Table 5.2 Ranking orders of DSR and DSDV

Number of streams	Ranking order	
	optimist	pessimist
2	DSR > DSDV	DSDV > DSR
6	DSDV > DSR	DSR > DSDV
10	DSDV > DSR	DSR > DSDV

5.5 Fuzzy preference programming method (FPP)

As an alternative to FGMM, FPP can also be used to rank DSDV and DSR.

5.5.1 Deriving weights

According to Mikhailov [182], the weights for metrics and alternatives can be obtained by solving a linear program

$$\text{maximise} \quad \lambda$$
$$\text{subject to} \quad \begin{cases} d_1\lambda + \omega_i - u_{ij}(\alpha)\omega_j \le d_1 \\ d_2\lambda - \omega_i + l_{ij}(\alpha)\omega_j \le d_2 \\ \sum_{i=1}^{n} \omega_i = 1 \end{cases} \tag{5.11}$$

where d_1 and d_2 denote tolerance parameters, λ symbolizes the consistency index and $u_{ij}(\alpha)$ and $l_{ij}(\alpha)$ are lower and upper bounds of α-cut intervals. It is suggested by Mikhailov that $d_1 = d_2 = 1$. If $\lambda \ge 1$, the comparisons are considered consistent.

In (5.11),

$$l_{ij}(\alpha) = \alpha(m_{ij} - l_{ij}) + l_{ij} \tag{5.12}$$

and

$$u_{ij}(\alpha) = \alpha(m_{ij} - u_{ij}) + u_{ij} \qquad (5.13).$$

where a_{ij}=(l_{ij}, m_{ij}, u_{ij}).

As seen in (5.12) and (5.13), the weights obtained from (5.11) depend on the value of α and thus they are considered to be a function of α. Mikhailov aggregates weights via

$$\omega_i = \frac{\sum_{i=1}^{L} \alpha_l \times \omega_i(\alpha_l)}{\sum_{i=1}^{L} \alpha_l} \tag{5.14}$$

where L denotes number of α values, α_l represents the l^{th} value for α and $\omega_i(\alpha_l)$ is the weight for a specific value of α.

Combining matrix (5.4) and (5.11)-(5.13), the α dependent weights for DSR and DSDV under the metric packet delivery ratio are obtained in Figure 5.6 for 2 streams. As shown, the weight for DSR increases with the increase of α. Finally, those α dependent weights are aggregated, denoted by DSDV-agg and DSR-agg. As observed, the aggregated weight for DSR is larger than that of DSDV, revealing that DSR outperforms DSDV in packet delivery ratio.

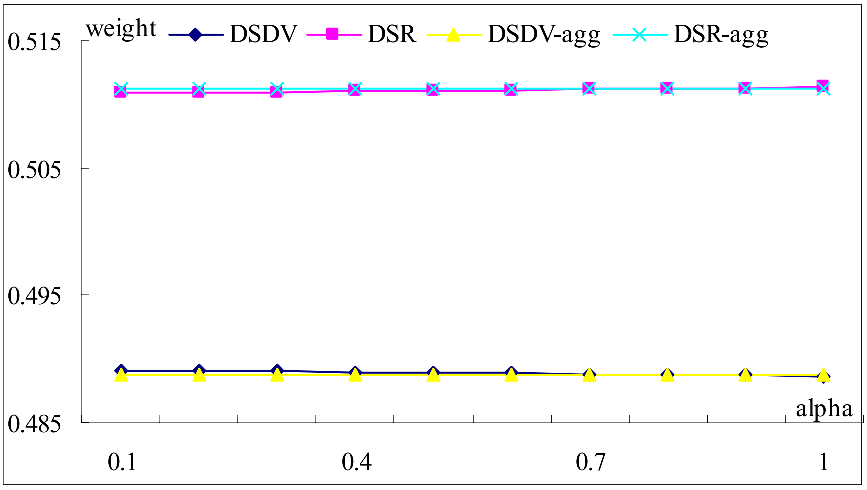


Figure 5.6 Alternative weights under packet delivery ratio (2 streams)

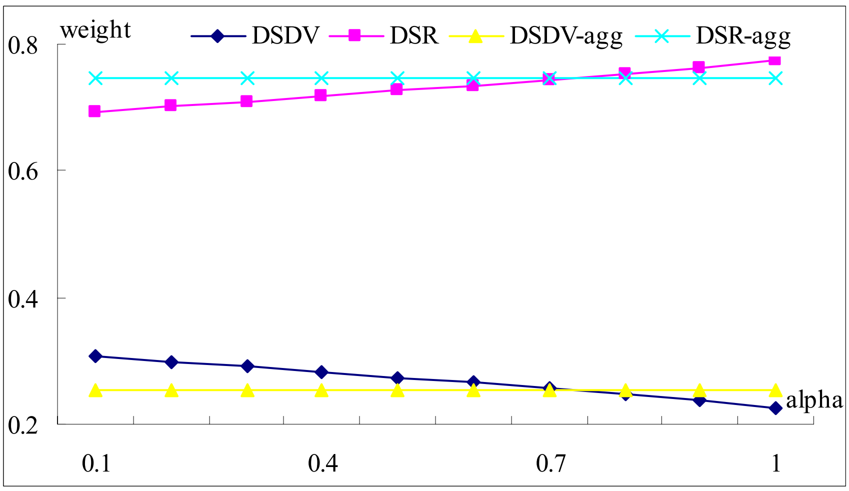


Figure 5.7 Alternative weights under energy cost (2 streams)

Combining matrix (5.8) and (5.11)-(5.13), the weights for DSDV and DSR can be computed and aggregated as shown in Figure 5.7. Similar to packet delivery ratio, the α dependent weight for DSR increases with the increase of α for the metric energy cost as shown in and the aggregated weight for DSR exceeds that of DSDV.

On the contrary, the weights for DSR under the metrics delay, jitter as well as throughput decrease with the increase of α, as shown in Figure 5.8, Figure 5.9 and Figure 5.10. The aggregated weights for DSR under the above three metrics are smaller than that of DSDV, indicating that DSDV outperforms DSR in delay, jitter and throughput.

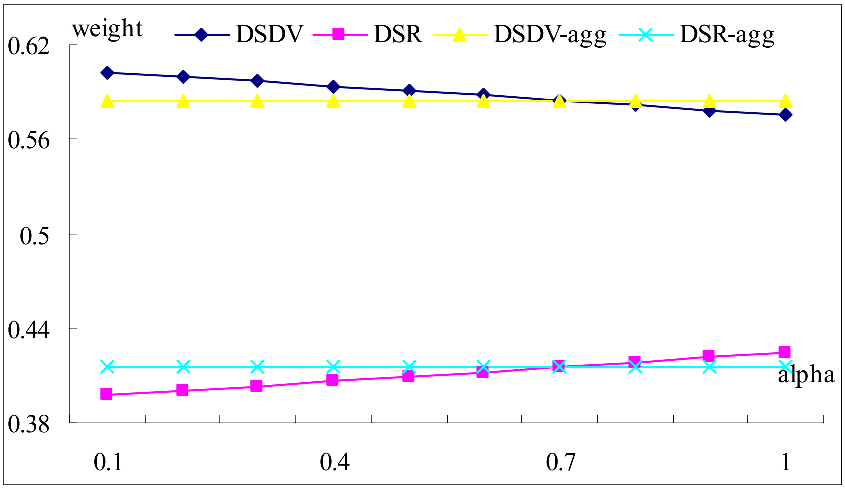


Figure 5.8 Alternative weights under delay (2 streams)

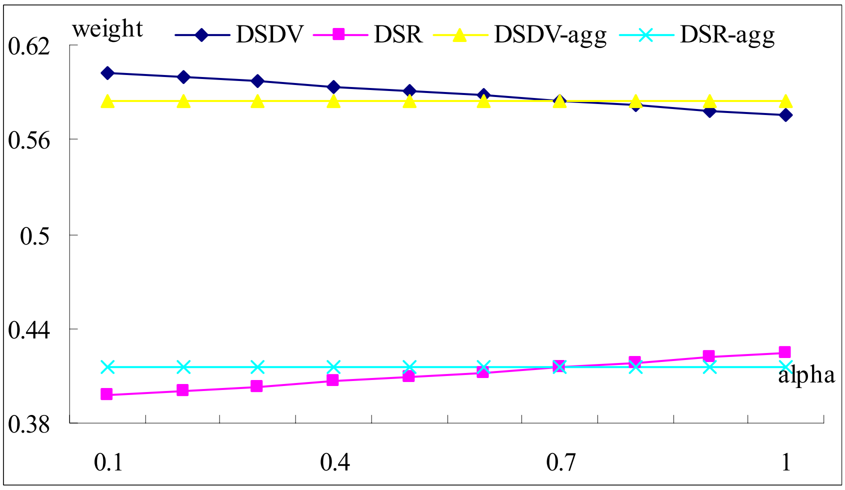


Figure 5.9 Alternative weights under jitter (2 streams)

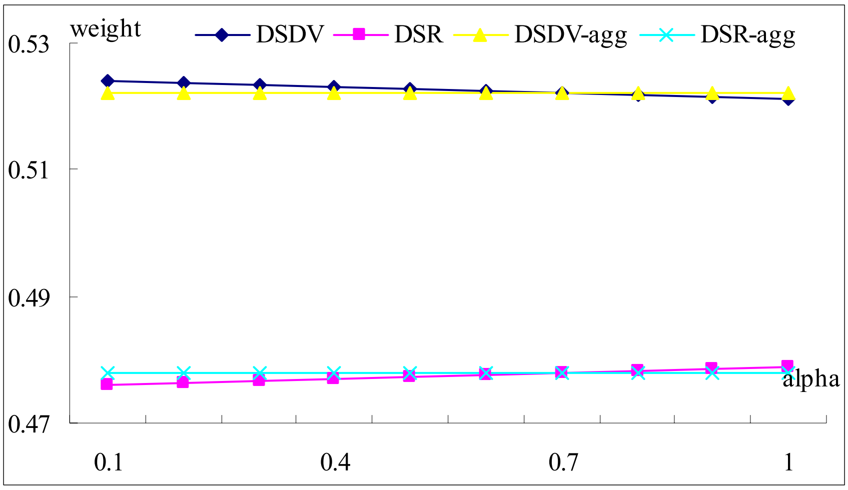


Figure 5.10 Alternative weights under throughput (2 streams)

These weights for DSDV and DSR are synthesized, using formula (4.16), and the result is shown in Figure 5.11. As shown, in the case of 2 traffic streams, DSR has a larger synthetic weight compared to DSDV and thus it is preferred. However, as the number of traffic streams increases, the weight for DSR declines and it is smaller than that for DSDV in both 6 and 10 streams and therefore DSDV is considered better in those two cases.

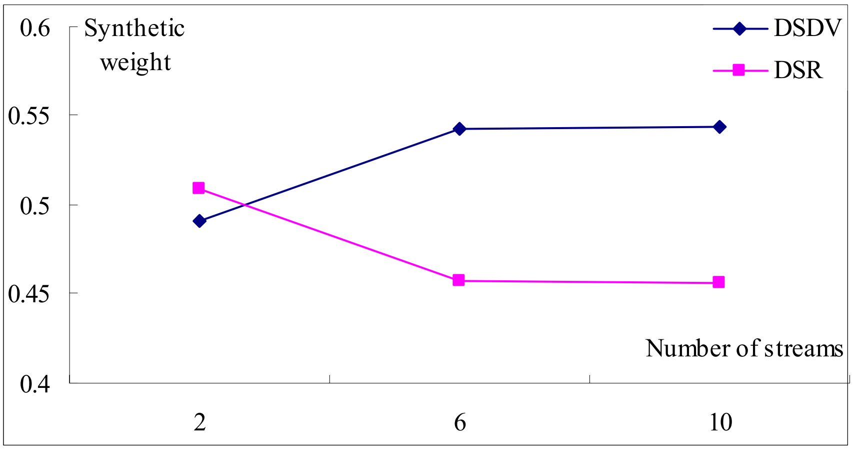


Figure 5.11 Synthetic weights for DSDV and DSR by FPP

Table 5.3 Ranking order by FPP

number of traffic flow	Ranking order
2	DSR > DSDV
6	DSDV > DSR
10	DSDV > DSR

5.5.2 Consistency measurement

Mikhailov [182] develops an aggregated consistency index λ to measure the reliability of the results.

$$\lambda_{agg} = \frac{\sum_{i=1}^{L} \alpha_i \times \lambda(\alpha_i)}{\sum_{i=1}^{L} \alpha_i} \tag{5.15}$$

A larger λ_{agg} indicates a more consistent matrix.

Figure 5.12 includes the consistency index values for the case of 2 traffic streams. As seen, the aggregated consistency index for the metric energy is the largest while that of packet delivery ratio is the smallest. It is also observed that all consistency indices exceed 1. According to Mikhailov [182], if λ_{agg}>1, the fuzzy matrix is considered consistent. Therefore, fuzzy matrices (5.4)-(5.8) are consistent for the case of 2 streams.

Similarly, aggregated consistency index values for the case of 6 and 10 streams are obtained and shown in Figure 5.13 and Figure 5.14. As observed, all consistency indices are larger than 1, indicating consistency of matrices for the case of 6 and 10 streams.

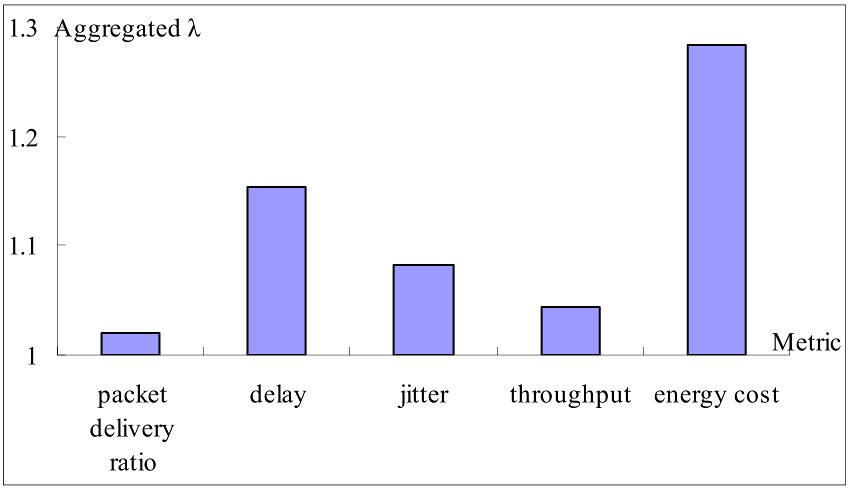


Figure 5.12 Consistency index (2 streams)

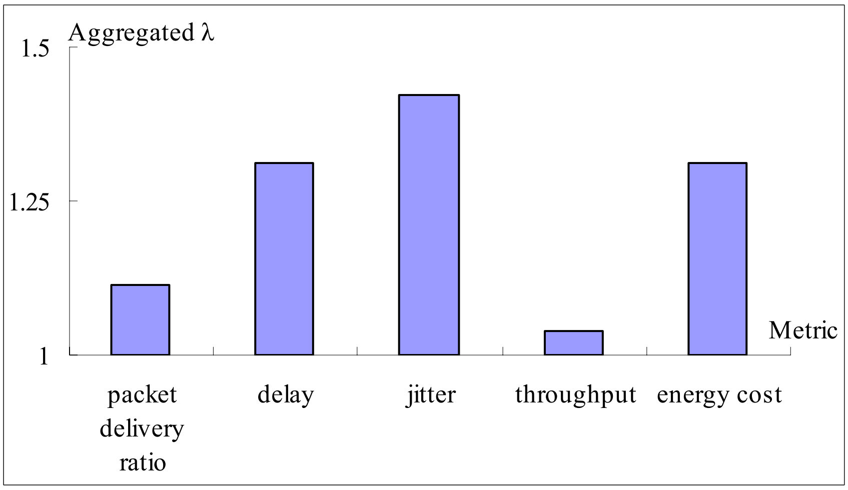


Figure 5.13 Consistency index (6 streams)

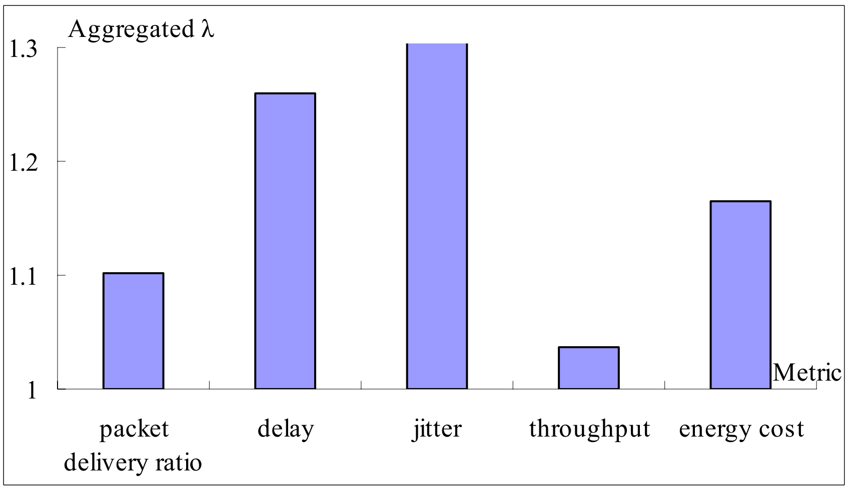


Figure 5.14 Consistency index (10 streams)

5.6 Fuzzy synthetic improvement ratio index (FSIRI)

In section 4.5, a metric SIRI is developed to measure the reliability and efficiency of the performance evaluation method. When standard deviations are considered, the SIRI is extended to FSIRI, using a method similar to formula (5.14). To begin with, the PIR is extended to FPIR by

$$FPIR_{ref-tar}(\alpha)=\frac{AP_{\text{target}}(\alpha)-AP_{\text{reference}}(\alpha)}{AP_{\text{reference}}(\alpha)}=\frac{AP_{\text{target}}(\alpha)}{AP_{\text{reference}}(\alpha)}-1 \qquad (5.16)$$

For metrics that are "the larger the better"

$$\begin{aligned} AP_{\text{target}}(\alpha) &= \frac{l_{ij}(\alpha)+u_{ij}(\alpha)}{2} \\ &= \alpha\times\Delta_{\text{target}}+a_{\text{target}} \end{aligned} \qquad (5.17)$$

$$\begin{aligned} AP_{\text{reference}}(\alpha) &= \frac{l_{ij}(\alpha)+u_{ij}(\alpha)}{2} \\ &= \alpha\times\Delta_{\text{reference}}+a_{\text{reference}} \end{aligned} \qquad (5.18)$$

where a_{target} and $a_{\text{reference}}$ are average performance of target and reference protocols respectively, $\Delta_{\text{reference}}$ and Δ_{target} denote corresponding standard deviations.

For "the smaller the better" metrics,

$$AP_{\text{target}}(\alpha) = \frac{l_{ij}(\alpha)+u_{ij}(\alpha)}{2}$$

$$= \frac{\alpha\times\left(\frac{1}{a_{\text{target}}}-\frac{1}{a-\Delta_{\text{target}}}\right)+\frac{1}{a-\Delta_{\text{target}}}\quad \alpha\times\left(\frac{1}{a_{\text{target}}}-\frac{1}{a+\Delta_{\text{target}}}\right)+\frac{1}{a+\Delta_{\text{target}}}}{2}$$

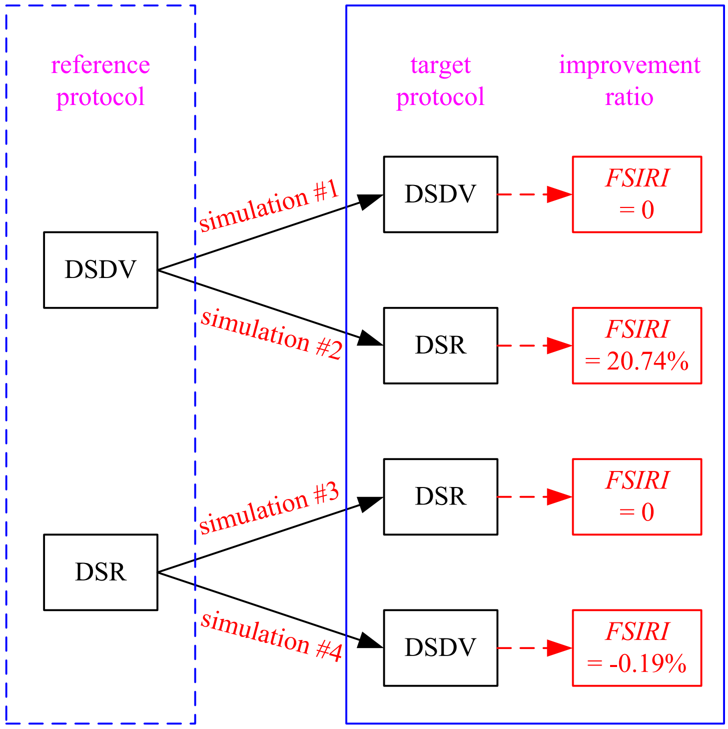
$$= \frac{\alpha}{a_{\text{target}}}+\frac{(1-\alpha)}{2}\left(\frac{1}{a+\Delta_{\text{target}}}+\frac{1}{a-\Delta_{\text{target}}}\right) \tag{5.19}$$

$$AP_{\text{reference}}(\alpha) = \frac{\alpha}{a_{\text{reference}}}+\frac{(1-\alpha)}{2}\left(\frac{1}{a+\Delta_{\text{reference}}}+\frac{1}{a-\Delta_{\text{reference}}}\right) \tag{5.20}$$

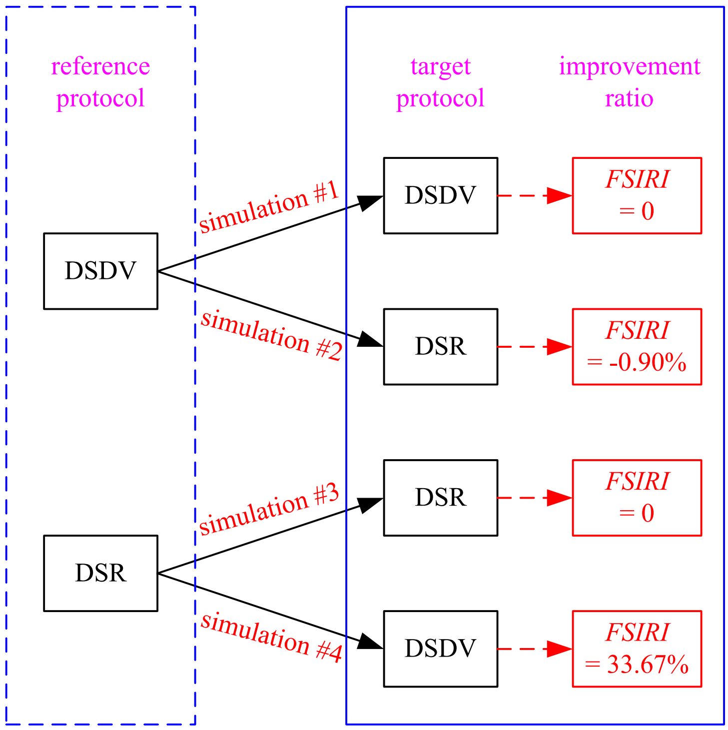
Similar to formula (4.32) and (4.33), FSIRI is obtained by aggregating FPIR values with weights for metrics:

$$FSIRI = \frac{\sum_{l=0}^{L}\left[\sum_{i=1}^{n} c_i \times FPIR(\alpha_l)\right]}{\sum_{l=0}^{L}\alpha_l} \tag{5.21}$$

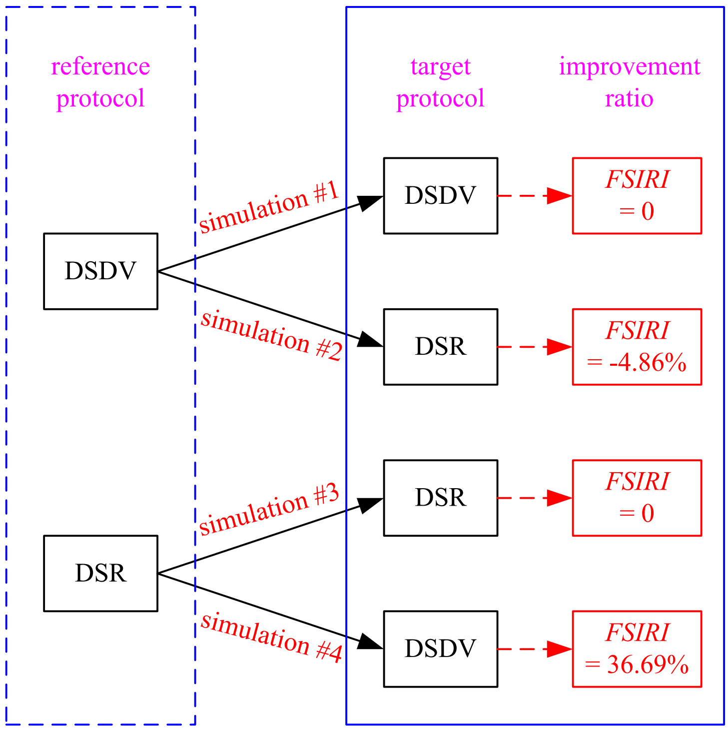
Figure 5.15 displays the FSIRI for 2, 6 and 10 traffic streams. As shown, a 20.74% gain can be achieved by switching DSDV to DSR for 2 streams. However, performance deterioration will be experienced if DSR is replaced by DSDV. As the number of traffic streams increases, DSDV behaves better. Gains of 33.67% and 36.69% are obtained by switch the previous DSR to DSDV. Therefore, it is concluded that DSR is suitable for 2 streams and DSDV performs better in case of 6 and 10 traffic streams as summarized in Table 5.4. As seen, results are identical to those obtained by SAW-FPP which validates reliability of the proposed SAW-FPP.



(a) 2 streams



(b) 6 streams



(c) 10 streams

Figure 5.15 FSIRI for different number of streams

Table 5.4 Ranking order by simulation

number of traffic flow	Ranking order
2	DSR > DSDV
6	DSDV > DSR
10	DSDV > DSR

5.7 Conclusion

SAW-AHP is extended to fuzzy SAW-AHP by considering standard deviations and thus the latter is more accurate. Two algorithms, FGMM and FPP, are applied to derive weights from fuzzy SAW-AHP comparison matrices. FGMM leads to fuzzy weights, which may result in different, sometimes contrary ranking orders and therefore it is abandoned. FPP is able to give crisp synthetic weights reliably based on which alternatives are ordered.

Figure 5.16 compares synthetic weights before and after the standard deviations are considered. As seen, the weights derived from fuzzy SAW-AHP using FPP method are larger than that derived from SAW-AHP in 2, 6 and 10 streams.

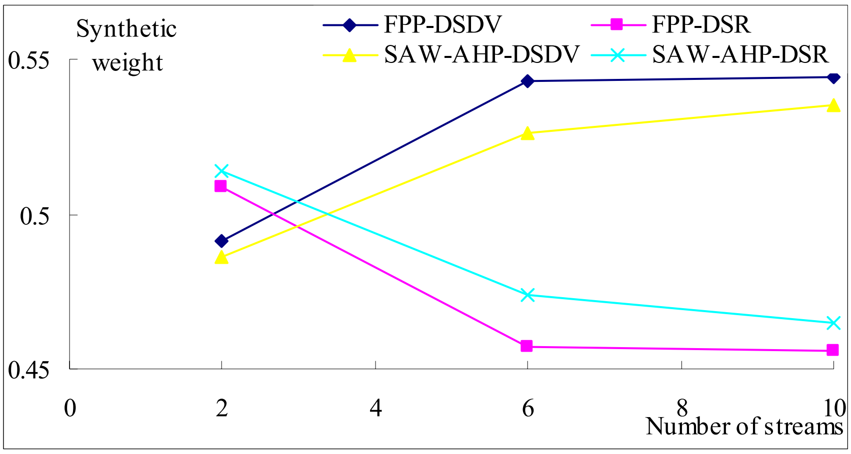


Figure 5.16 Comparison of fuzzy SAW-AHP and SAW-AHP

However, the distance of weights using FPP and SAW-AHP varies in different streams. It is observed that the distance depends on the ratio of standard deviation over average value (RSDA). Averagely, RSDA of 6 streams are much larger than that of 2 streams and therefore weights using FPP and SAW-AHP are closer compared to those of 6 streams. Likely, weights of DSDV in 10 streams are closer compared to 6 streams, but farther than that of 2 streams. Similar relationship also holds for DSR. It is hence concluded that the distance between FPP and SAW-AHP depends on the ratio of standard deviation over average value

Table 5.5 Ratio of standard deviation over average value

Metric	2 streams			6 streams			10 streams		
	avg	std	std/avg	avg	std	std/avg	avg	std	std/avg
PDR (%)	94.7	2.58	**0.027**	69.1	8.00	**0.12**	65.7	7.23	**0.11**
Delay (s)	1.98	0.235	**0.12**	3.63	1.01	**0.28**	3.58	0.745	**0.21**
Jitter (s)	2.41	0.155	**0.064**	4.01	1.67	**0.42**	4.37	1.18	**0.27**
Thruput (Mb/s)	3.68	0.115	**0.031**	3.57	0.097	**0.026**	3.55	0.091	**0.026**
EC (J/pkt)	0.73	0.201	**0.28**	0.290	0.070	**0.24**	0.256	0.040	**0.16**
avg: average value; std: standard deviation									

Chapter 6 Conclusions and Future work

This thesis has contributed to the development of performance evaluation algorithms over MANETs according to the users' preference of multiple QoS metrics. An adaptive model is incorporated into the current mobile ad hoc networks and the existing WLANs to provide a solution for the last mile access problems. Research results are summarized, contributions are highlighted and potential future research guidelines are discussed in this concluding chapter.

6.1 Summary

Mobile ad hoc networks are characterized by the absence of predefined infrastructure, limited energy supply and frequently changing network topology. Such networks were initially regarded as valuable in areas such as military or search-and-rescue operations. With the increasing popularity of real-time applications, some best effort routing protocols proposed previously are unable to provide quality of service (QoS) support. Several QoS provision algorithms have been proposed which support one or two metrics, always in terms of delay and/or bandwidth. QoS is not strictly supported in those algorithms. Providing support for at least two QoS metrics is necessary in many practical applications but optimising this is an NP-complete problem.

A best effort QoS support model (BEQoS) is proposed in this thesis, relaxing the strict QoS requirement. In this model, alternative protocols are evaluated and ranked so that the best protocol can be selected under a given QoS preference. BEQoS in this thesis has two algorithms, SAW-AHP and FPP. The first one deals with case where user is certain with his/her preference over QoS metrics while the latter considers the uncertainty of the problems such as standard deviation..

In SAW-AHP, metrics are compared pair-wisely to obtain comparison matrices. A geometric mean method is applied to derive weights from those matrices. Similarly, weights for alternative protocols under different metrics are computed. Weights for metrics are aggregated with those for alternatives under metrics to achieve the final ranking order of the alternative protocols. Simulation results validate the reliability of SAW-AHP.

SAW-AHP is straight forward and easy to implement but it doesn't take factors such as standard deviation and uncertainty of human beings into consideration, leading to the inaccuracy of the ranking results. To solve this problem, SAW-AHP is extended to fuzzy SAW-AHP, using fuzzy triangular numbers to incorporate the standard deviation in simulations. The reliability FPP is demonstrated by simulation.

An adaptive model based on SAW-AHP is proposed to solve the last mile access problem. The adaptive model include three components, protocol selection trigger which activates the protocol selection process, protocol selection decision which aggregates all user's QoS preference and determines the optimal protocol as well as protocol selection execution. All nodes in the network switch to the optimal protocol determined by the access point to realize network optimization.

6.2 Future research areas

There are several areas of this thesis that can be extended through future research. They are outlined as follows:

(I) The evaluation method described in Chapter 4 and Chapter 5 is based on a single decision maker. A group decision method may be incorporated into SAW-AHP and FPP to decrease the impact of uncertainty of one decision maker on the final results and thereby increase the credibility.

(II) The costs such as increase of processor load, additional traffic induced congestion and more energy consumption that are caused by the application of the proposed adaptive algorithm in the integrated model in this thesis could be measured in practical implementations. If the gains of the adaptive algorithm exceed the costs, protocols should be switched accordingly and the network performance will be improved.

(III) In the future, multiple access techniques such as Bluetooth and MANETs, will be more commonly provided in the same equipment. QoS requirements have to be satisfied in those applications where the proposed BEQoS based adaptive algorithm is able to select the optimal solution.

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Appendix A: Rayleigh fading model

(1) Probability density function

The Rayleigh probability density function is

$$f(x,\ \sigma) = \frac{x}{\sigma^2}\ e^{-\frac{x^2}{2\sigma^2}}$$

where $x \in [0, \infty)$.

(2) Implementation in NS-2.32

signal strength without any fading

Pr0 = Friis(t->getTxPr(), Gt, Gr, lambda, L, dist0_) ;

Rayleigh fading factor

$$fadingfactor = \sigma \times \sqrt{-2 \times \ln(1 - uniform(0,\ 1))}$$

signal strength after Rayleigh fading

Pr = Pr0 * pow(10.0, powerLoss_db/10.0)**fadingfactor*

Appendix B: Stationary node position generation

It takes three steps to generate the stationary node positions and they are as follows.

(I) Generate two sets of two-dimensional coordinate (x1, y1) and (x2, y2) that are uniformly distributed on the topology;

(II) Let

$$r = \frac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}{\sqrt{2}}$$

and compare r with a random number U1 which is uniformly distributed between 0 and 1. If U1 < r, accept (x1, y1) and (x2, y2), otherwise, go to step (I);

(IV) The initial coordinate for the one node is

$$x = U_2 x_1 + (1 - U_2) x_2$$
$$y = U_2 y_1 + (1 - U_2) y_2$$

where U2 denotes another random variable uniformly distributed between 0 and 1;

Appendix C: simulation results (empirical knowledge)

Performance results (2 flows)

metric	DSDV		DSR	
	Average	Standard deviation	Average	Standard deviation
PDR (%)	94.7	2.58	99.1	1.40
delay (ms)	1.98	0.235	2.68	0.45
jitter (ms)	2.41	0.155	2.91	0.234
throughput (Mb/s)	3.68	0.115	3.38	0.178
energy cost (J/pkt)	0.73	0.201	0.214	0.051

Performance results (6 flows)

metric	DSDV		DSR	
	Average	Standard deviation	Average	Standard deviation
PDR (%)	69.1	8.00	85.0	7.60
delay (ms)	3.63	1.01	7.88	2.15
jitter (ms)	4.01	1.67	13.9	3.44
throughput (Mb/s)	3.57	0.097	3.29	0.172
energy cost (J/pkt)	0.290	0.070	0.169	0.049

Performance results (10 flows)

metric	DSDV		DSR	
	Average	Standard deviation	Average	Standard deviation
PDR (%)	65.7	7.23	82.4	6.33
delay (ms)	3.58	0.745	9.85	2.80
jitter (ms)	4.37	1.18	14.4	4.23
throughput (Mb/s)	3.55	0.091	3.25	0.153
energy cost (J/pkt)	0.256	0.040	0.185	0.025

Appendix D: weights for alternatives (6 and 10 streams)

Weights for alternatives (6 streams)

Criterion	Weights	
	DSDV	DSR
packet delivery ratio	0.448	0.552
delay	0.685	0.315
jitter	0.776	0.224
throughput	0.520	0.480
energy cost	0.368	0.632

Weights for alternatives (10 streams)

Criterion	Weights	
	DSDV	DSR
packet delivery ratio	0.444	0.556
delay	0.733	0.267
jitter	0.767	0.233
throughput	0.522	0.478
energy cost	0.420	0.580